Belle

(recent and coming results)

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for the Belle collaboration

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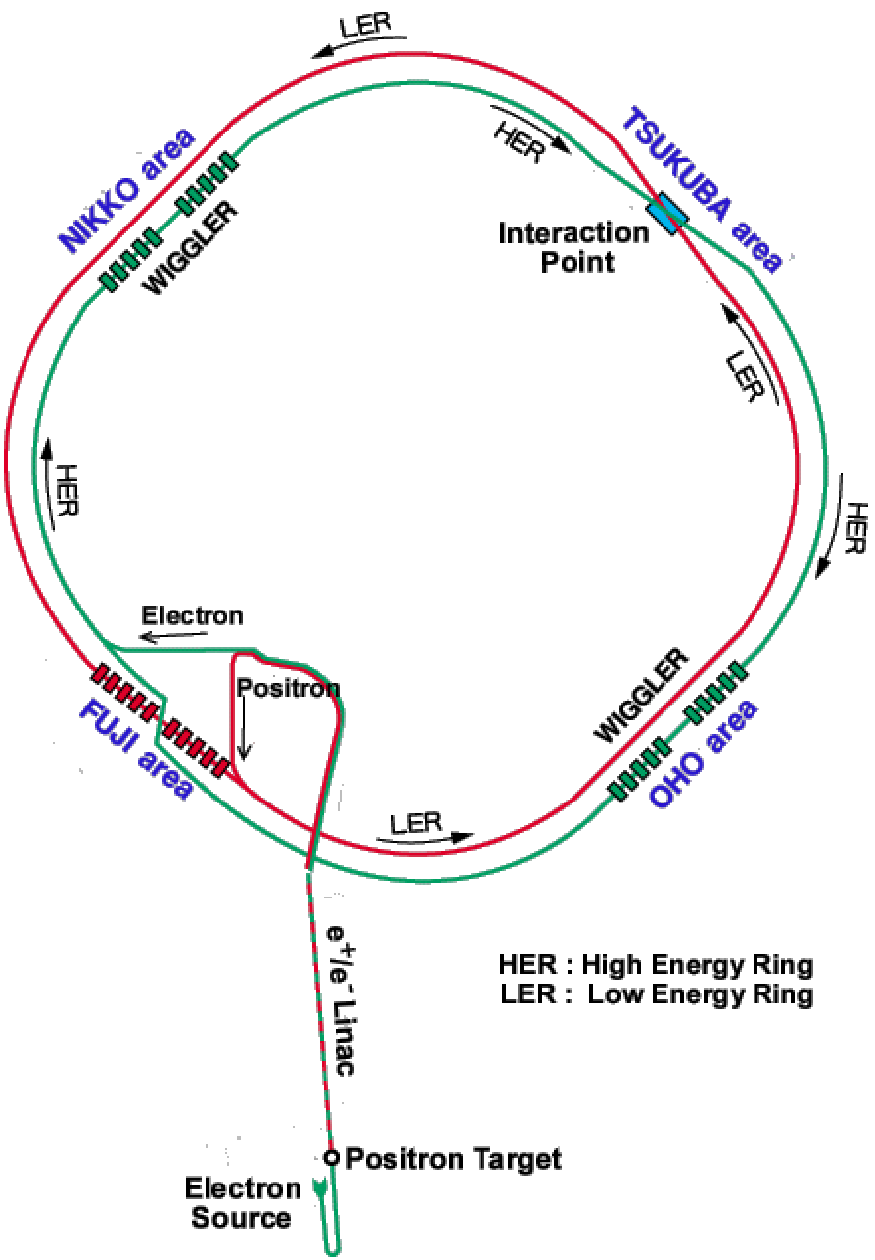
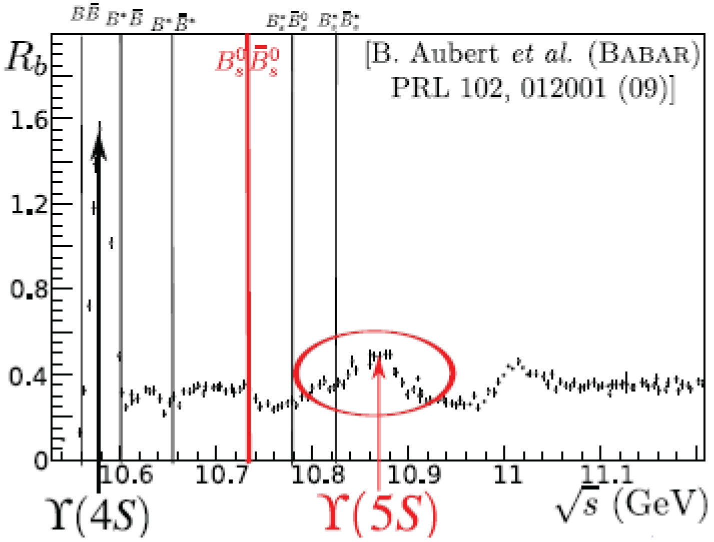
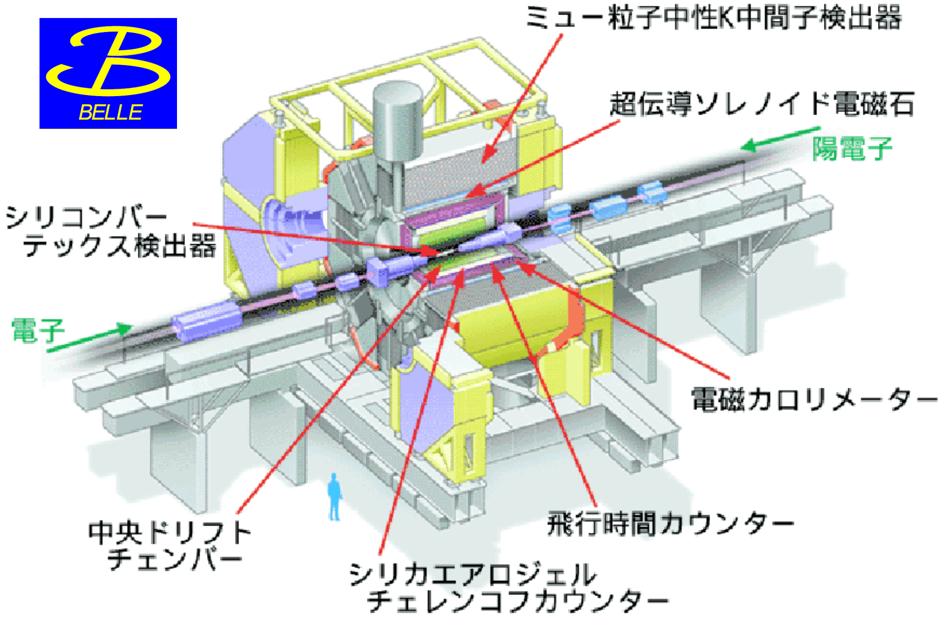
KEKB collider and Belle in a nutshell



HER : High Energy Ring
LER : Low Energy Ring



Belle is an international collaboration
15 countries, 64 institutes
365 members

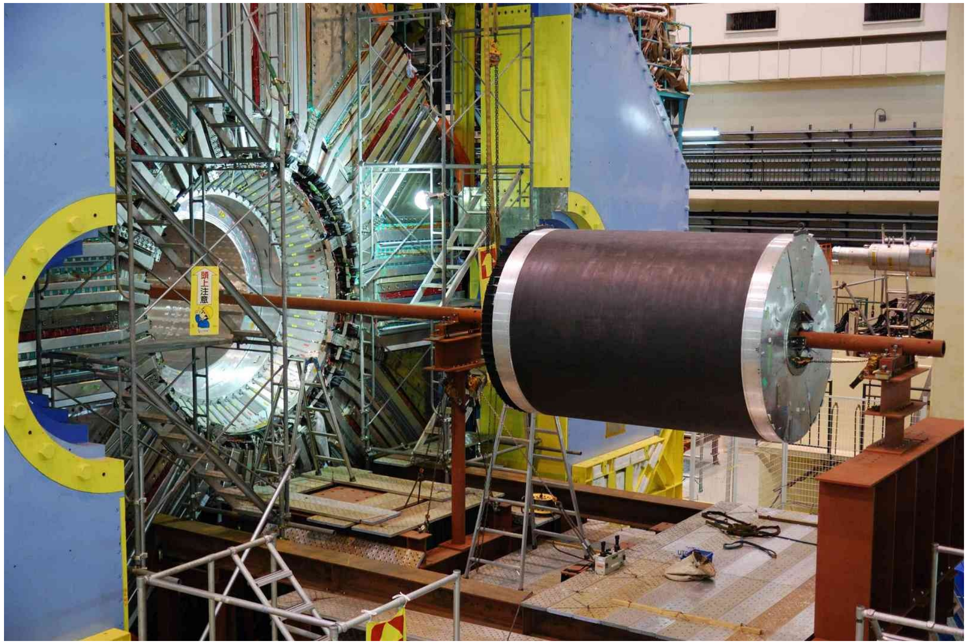


Belle shutdown last June (2010)

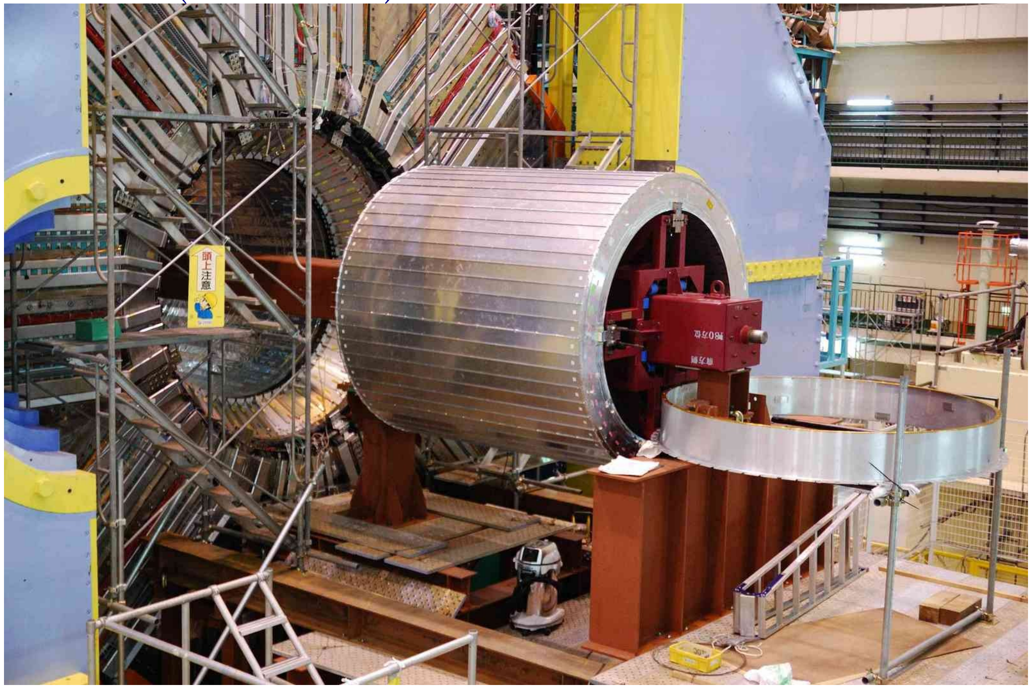
Belle these days...

ECL (backward endcap)

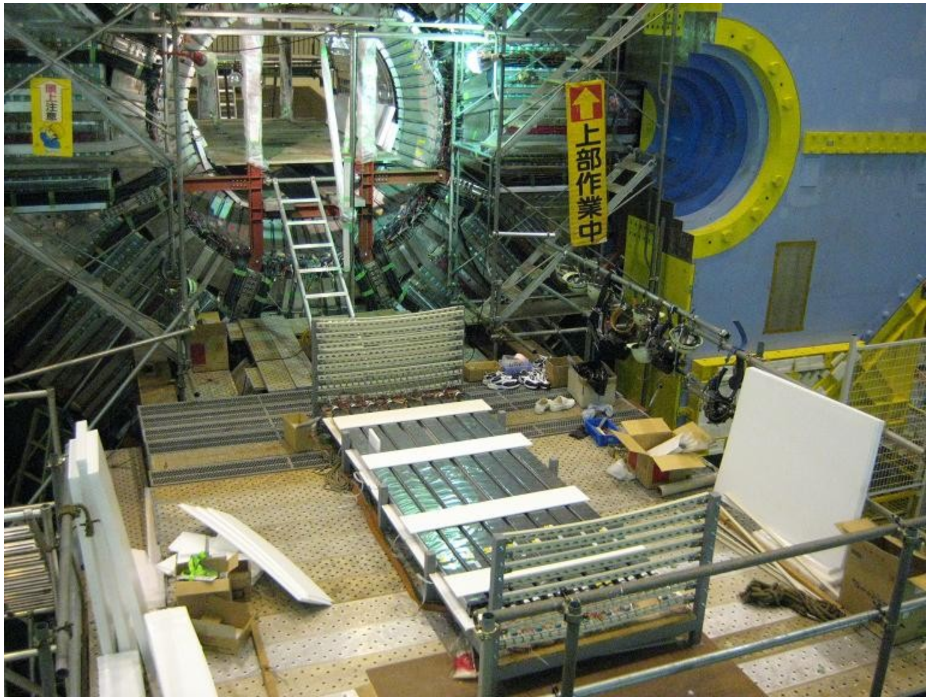
CDC



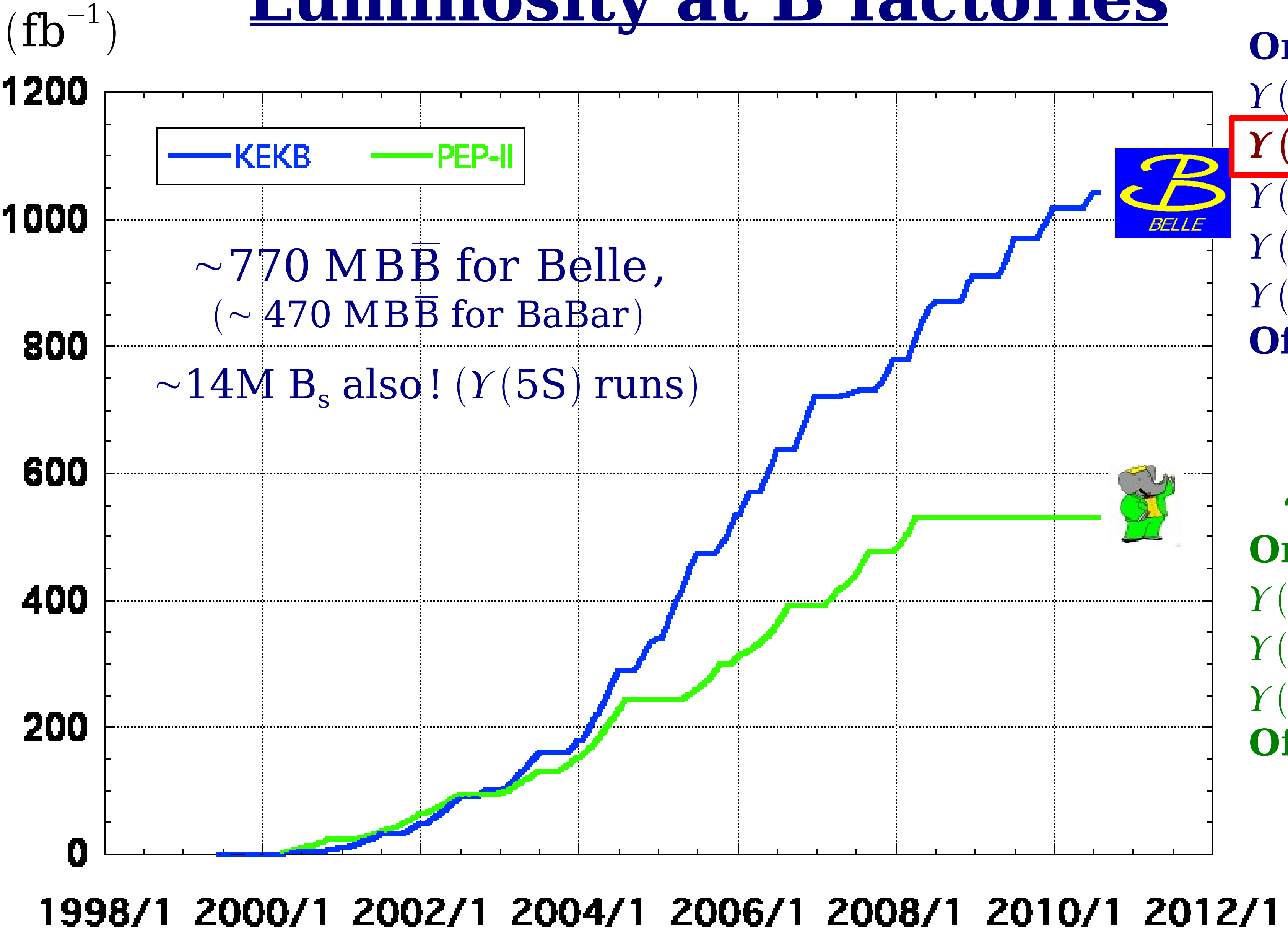
ACC (barrel)



TOF



Luminosity at B factories



~770 M$B\bar{B}$ for Belle,
(~ 470 M$B\bar{B}$ for BaBar)

~14M B_s also! ($\Upsilon(5S)$ runs)

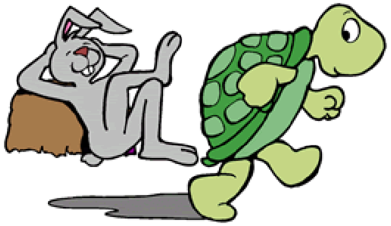
> 1 ab^{-1}

On resonance:
$\Upsilon(5S)$: 121 fb^{-1}
$\Upsilon(4S)$: 711 fb^{-1}
$\Upsilon(3S)$: 3 fb^{-1}
$\Upsilon(2S)$: 24 fb^{-1}
$\Upsilon(1S)$: 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

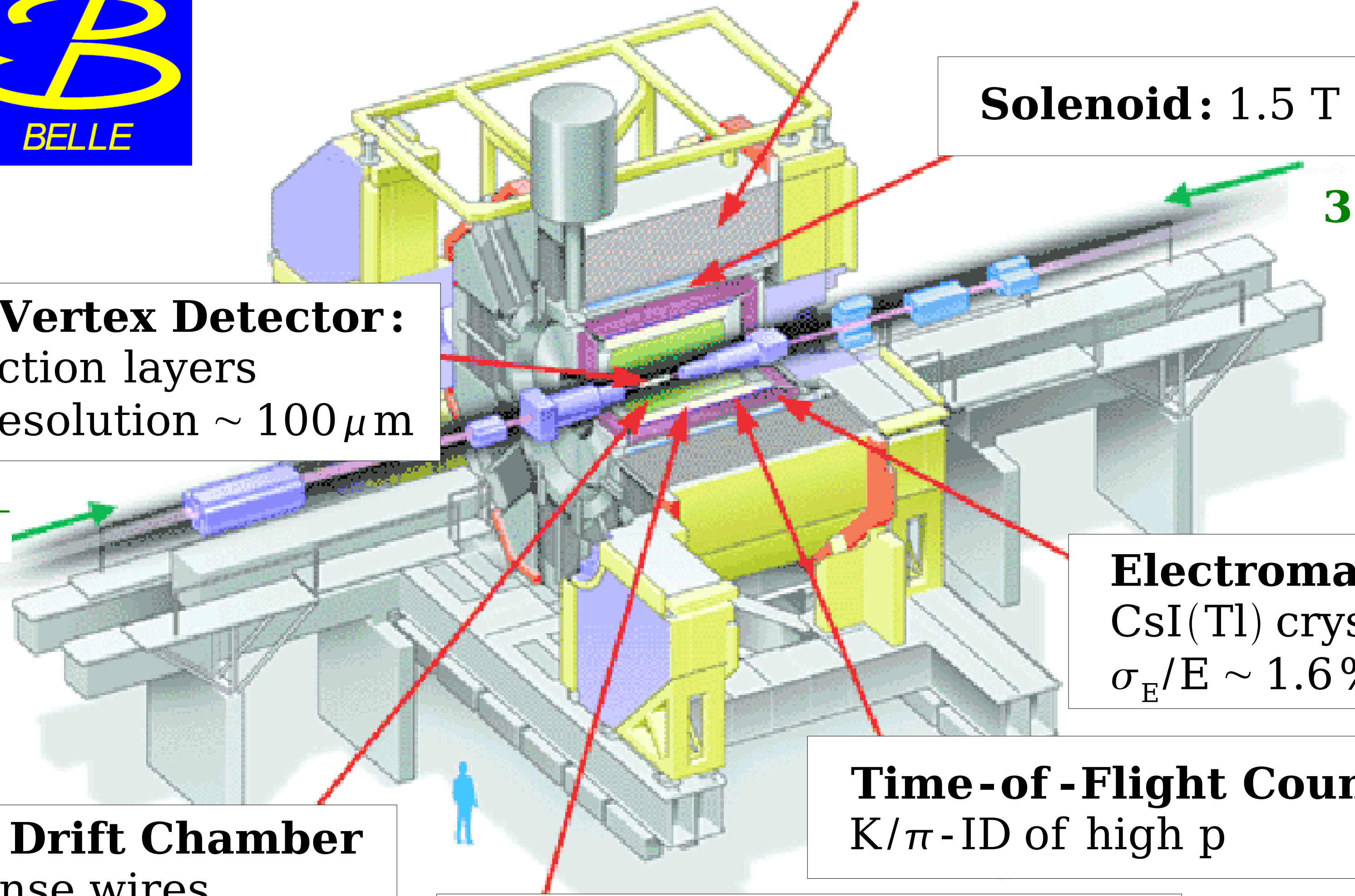
~ 550 fb^{-1}

On resonance:
$\Upsilon(4S)$: 433 fb^{-1}
$\Upsilon(3S)$: 30 fb^{-1}
$\Upsilon(2S)$: 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

Rien ne sert de courir ; il faut partir a point.
Le Lievre et la Tortue en sont un temoignage.
Gageons, dit celle-ci, que vous n'atteindrez point
Si tot que moi ce but. Si tot ? Etes-vous sage ?
Repartit l'Animal leger...



Belle in a nutshell



KLM ($K_L\mu$) Detector: Sandwich of 14 RPCs and 15 iron plates

Solenoid: 1.5 T

Silicon Vertex Detector:
3/4 detection layers
Vertex resolution ~ 100 μm

Electromagnetic Cal:
CsI(Tl) crystal
$\sigma_E/E \sim 1.6\%$ @ 1 GeV

Time-of-Flight Counter:
K/π-ID of high p

Central Drift Chamber
8,400 sense wires
PID with dE/dx

Aerogel Cerenkov Counter:
Refractive index n=1.01-1.03
K/π of middle p

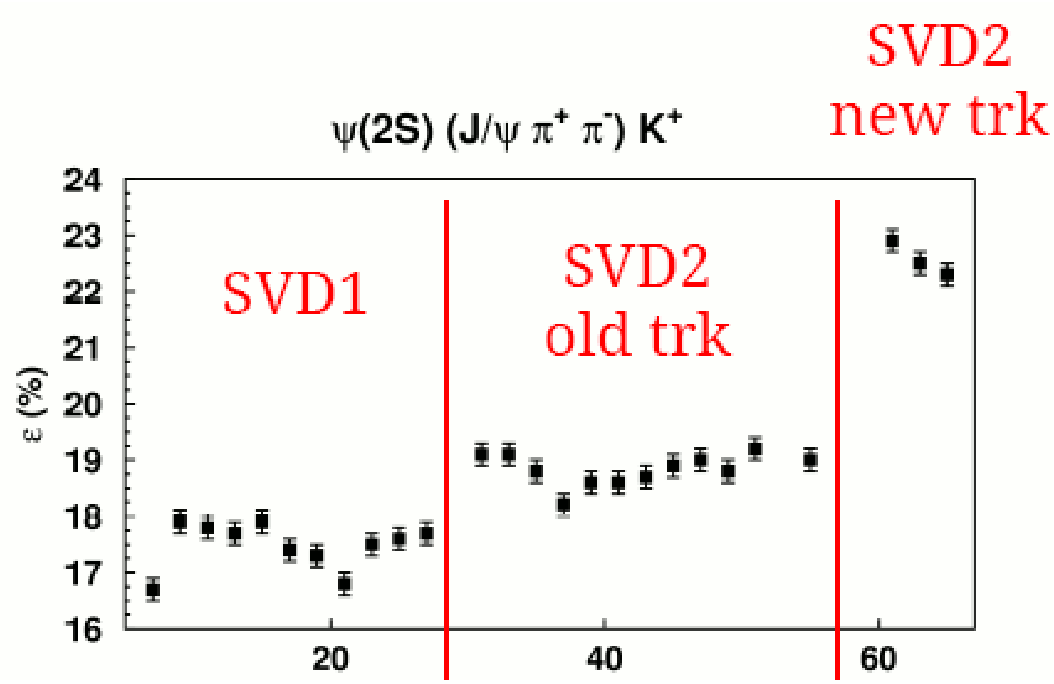
very stable detector, good particle identification, (kaon, pion, electron, muon),

e^+e^- is a clean environment: excellent tracking, triggering, tagging...

Toward the final Belle results...

- ◦ include the last part of the data (> 100 fb^{-1}, often much more...)
- ◦ reprocessed data (~ 2/3 of the data, tracking efficiency increase > 20%)

Efficiency for $B^+ \to \psi(2S)\,(J/\psi\,\pi\pi)K^+$



reconstruction systematics improved:

tracking efficiency systematics at high P_t

1.2% → 0.35% (update)

K_S: 4.5% → 2%

π^0: 4% → ??

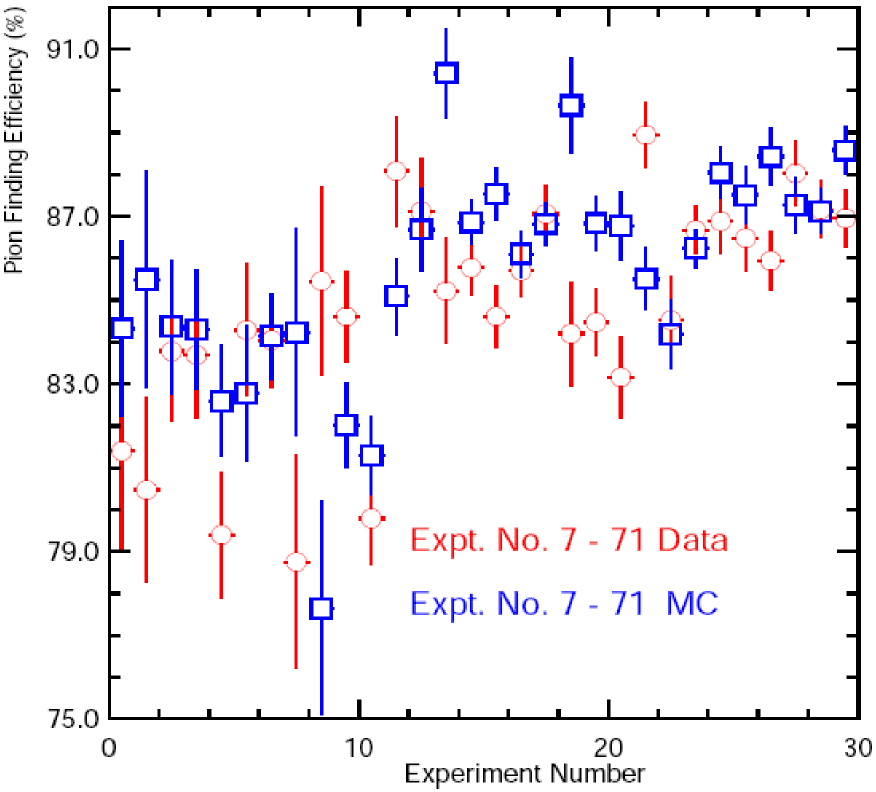
Example of $D \to K_S \pi\pi$

0.5M signal candidates in 540 fb^{-1}

PRL 99, 131803 (2007)

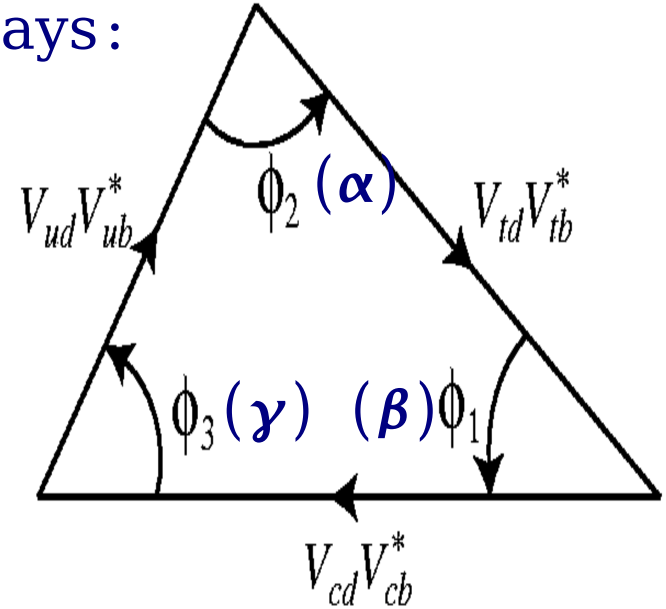
status of the update:

1.1M signal candidates in 790 fb^{-1}

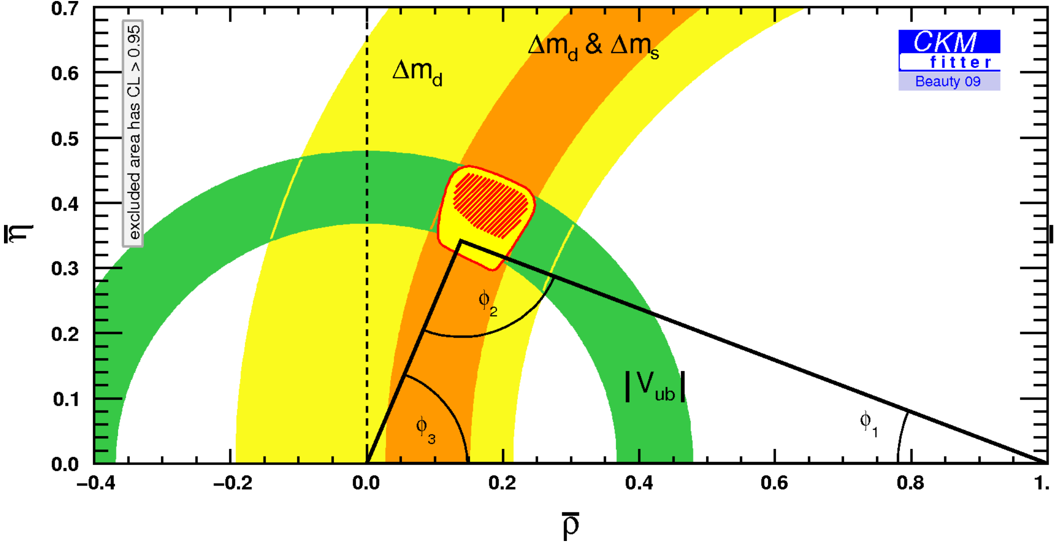


Main motivation of Belle

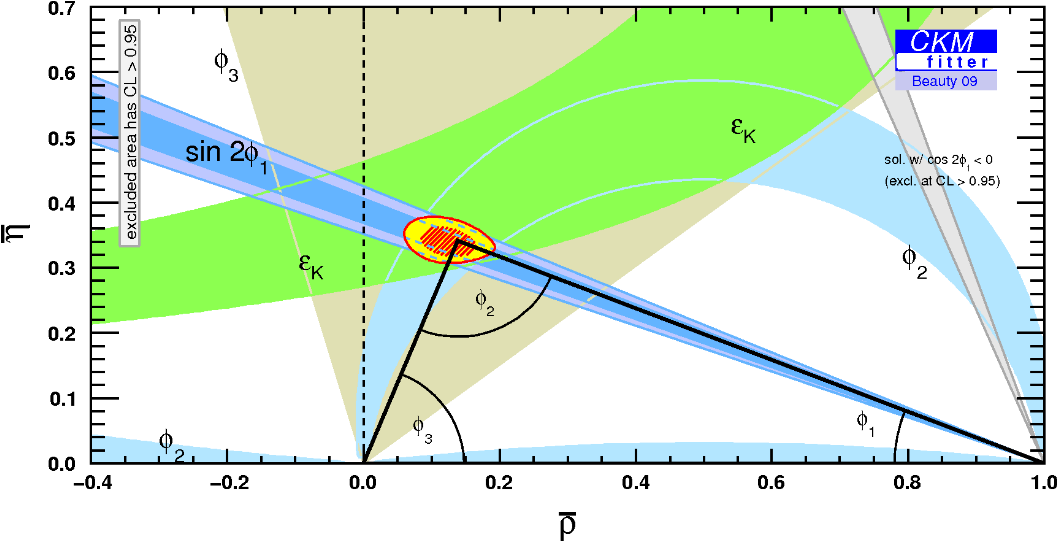
- Overconstrain the CKM matrix: measure fundamental parameters, constrain new physics effects
- Measure the 4 free paremeters in various ways:
  - CP conserving $\{|V_{us}|, |V_{cb}|, |V_{td}|, |V_{ub}|\}$
  - CP violating $\{\epsilon_K, \phi_s, \phi_{1,} \phi_3\}$
  - Tree level $\{\ldots, \ldots, |V_{ub}|, \phi_3\}$
  - Loop level $\{\ldots, \ldots, |V_{td}|, \phi_1\}$
  - …



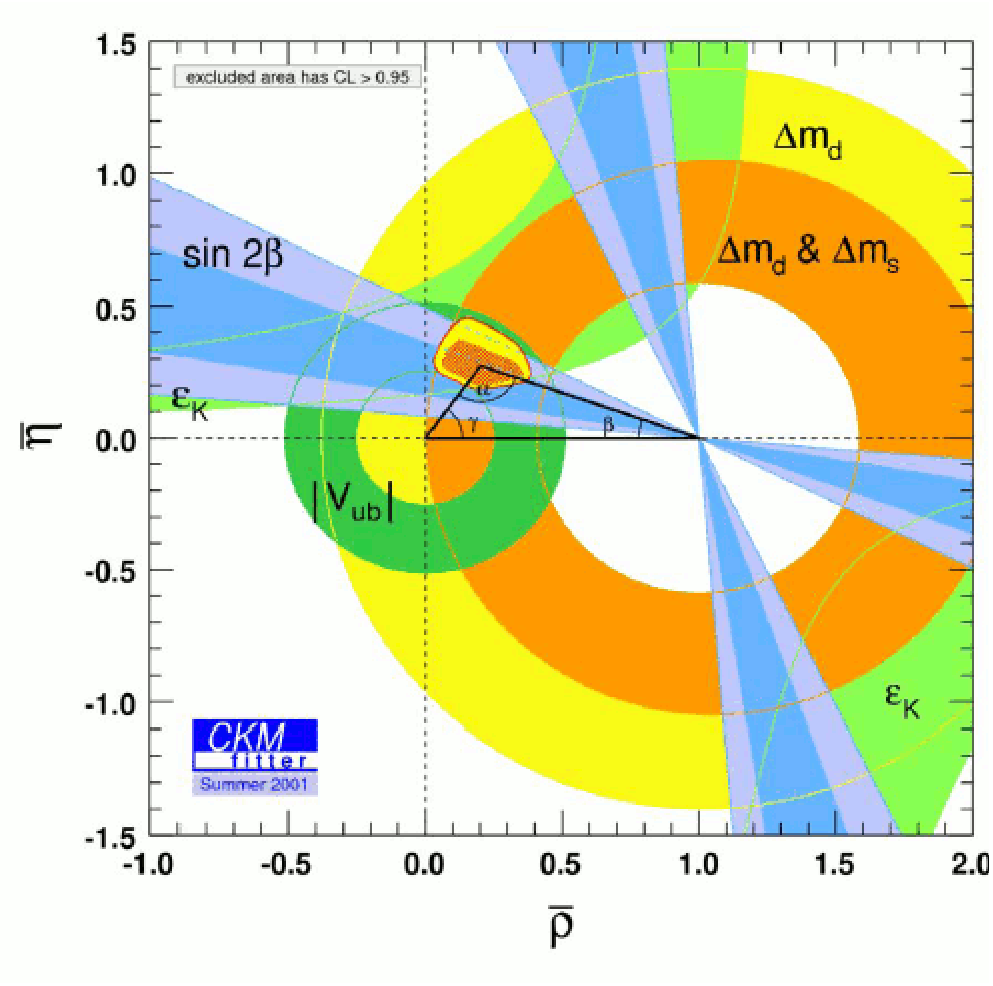
CP conserving



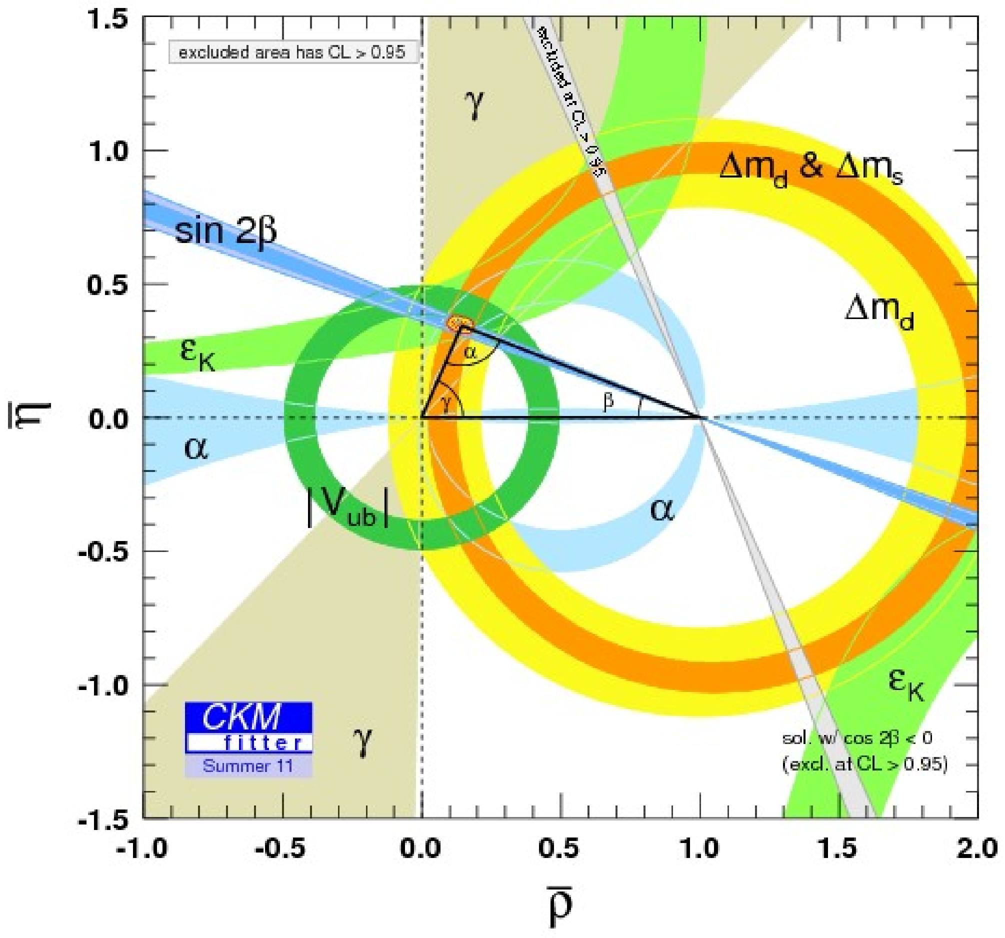
CP violating



from EPS 2001…

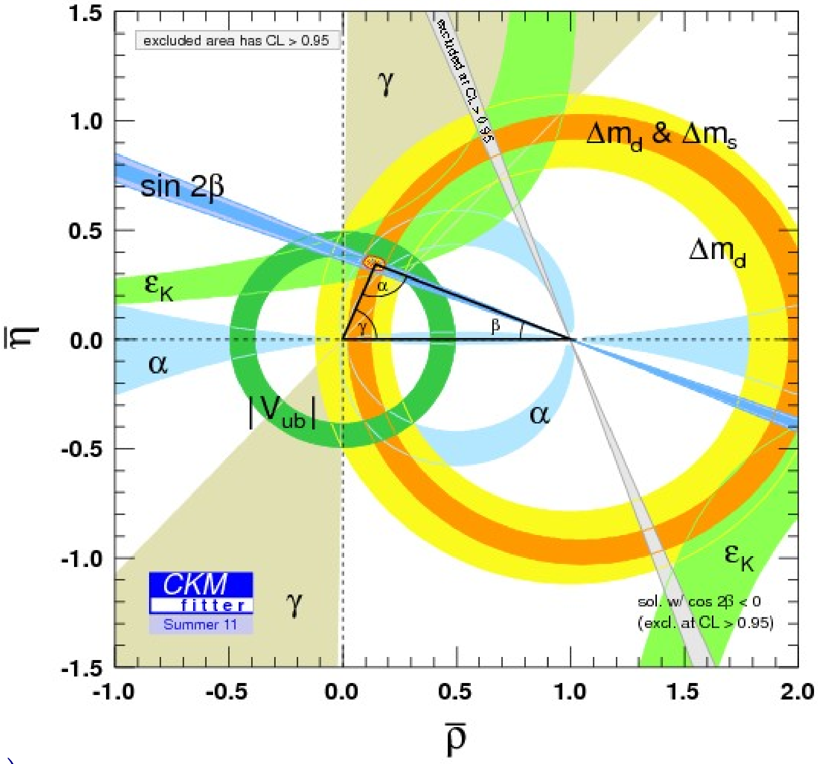


…to LP 2011



⇒ clear impact on B-factories (angles and sides) !

Outline



Recent updates for UT:

ϕ_1/β: $b \to c\bar{c}s$, $b \to c\bar{c}d$

ϕ_3/γ: $B^+ \to DK^+$

$B \to \tau\nu$

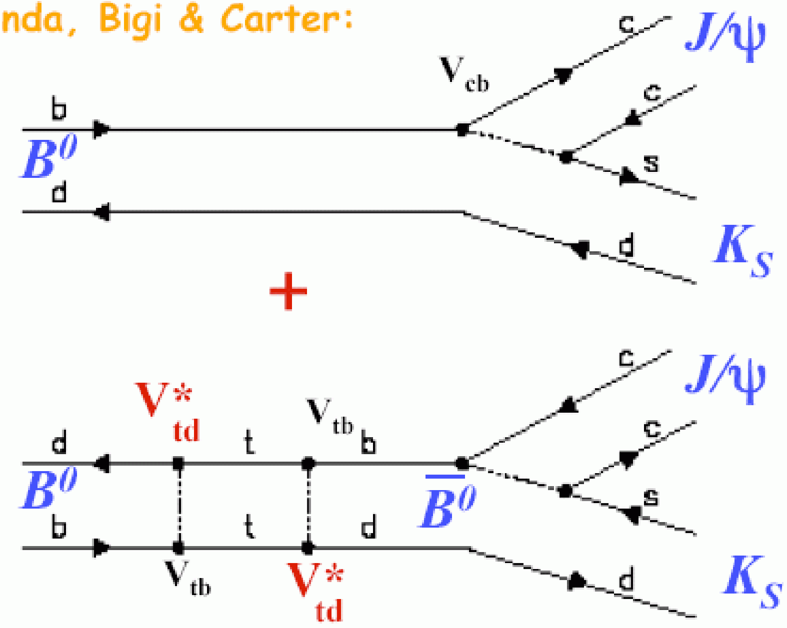
(and modes with missing energy)

Physics at $\Upsilon(5S)$: B_s and bottomonium

Time-dependent CP asymmetries in decays to CP eigenstates

sin2ϕ_1 from $B \to f_{CP} + B \leftrightarrow \overline{B} \to f_{CP}$ interf.

Sanda, Bigi & Carter:



$$A_{CP}(f;t) = \frac{N(\overline{B}^0(t) \to f) - N(B^0(t) \to f)}{N(\overline{B}^0(t) \to f) + N(B^0(t) \to f)}$$

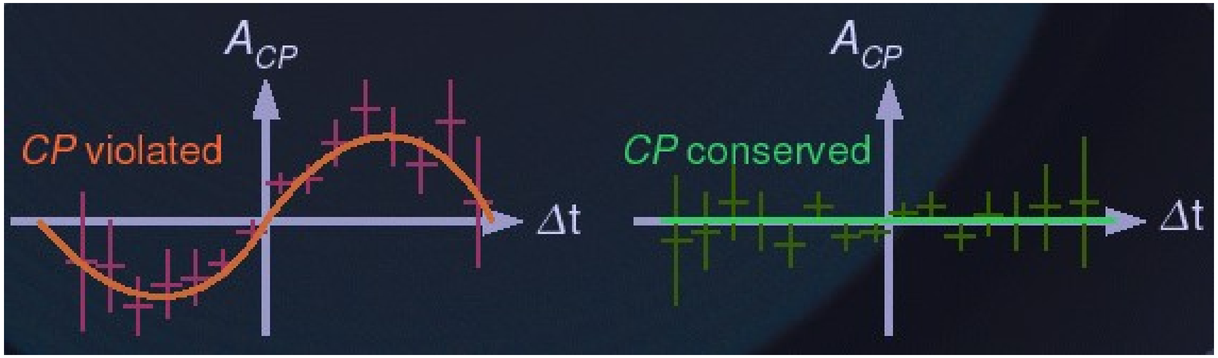
$$= \mathbf{S} \sin \Delta m_d t + \mathbf{A} \cos \Delta m_d t$$

$$= \frac{2 \operatorname{Im} \lambda}{|\lambda|^2 + 1} \sin \Delta m_d t + \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \cos \Delta m_d t$$

$$\lambda = \frac{q}{p} \frac{A(\overline{B}^0 \to f)}{A(B^0 \to f)} = e^{-i2\phi_i} \frac{\overline{A}_f}{A_f}$$

○ $\mathbf{A} = 0$ and $\mathbf{S} = -\xi_f \sin 2\beta$ for $(c\bar{c})K_{S/L}$ $(\xi_f = \mp 1)$

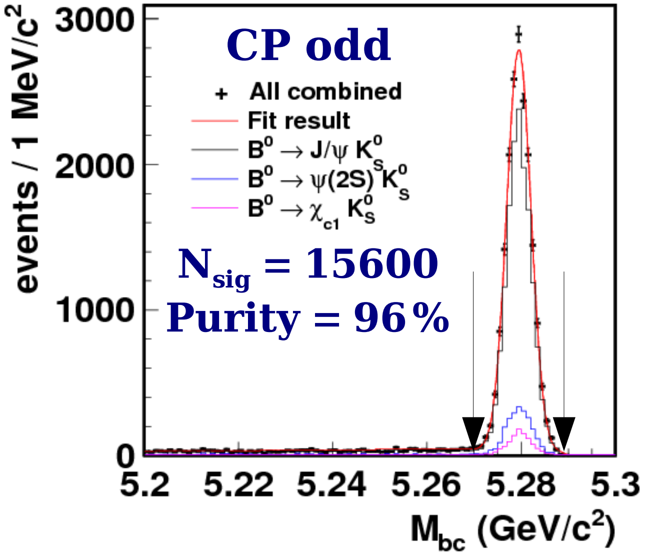
○ $\mathbf{A} = 0$ and $\mathbf{S} = \sin 2\alpha$ for $\pi^+ \pi^-$ (if tree only)

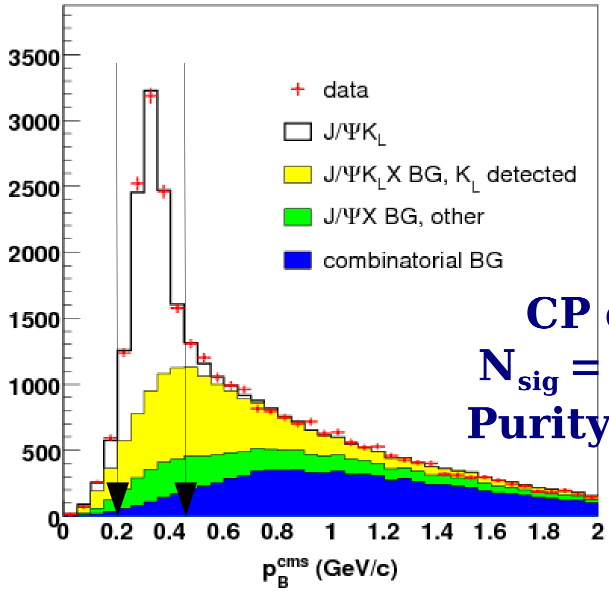


$$\mathbf{C = -A}$$

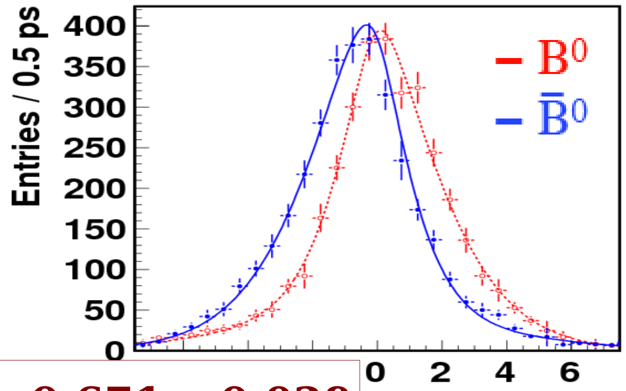
$c\bar{c}$ K_S and J/ψ K_L

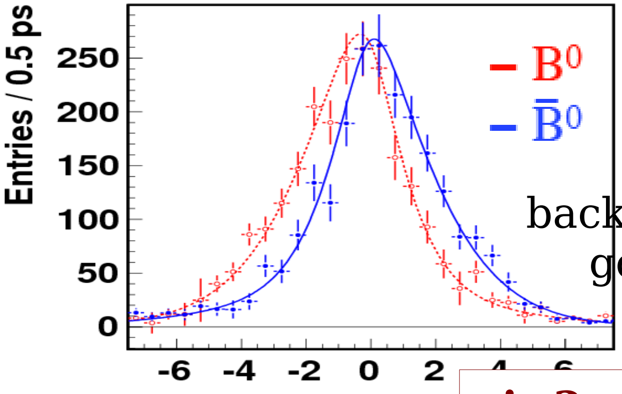
772×10^{6} $B\bar{B}$ pairs





CP even
N_{sig} = 10041
Purity = 63%

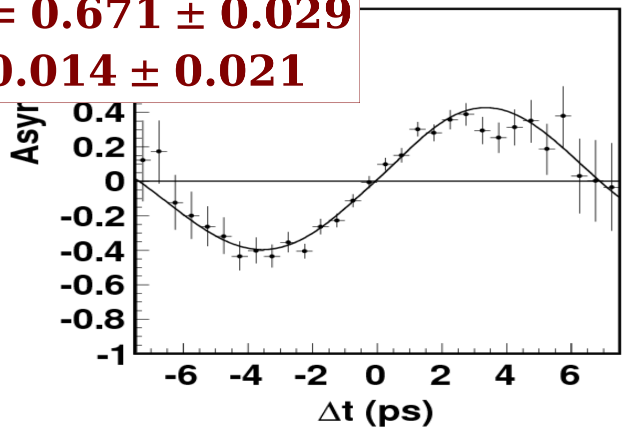


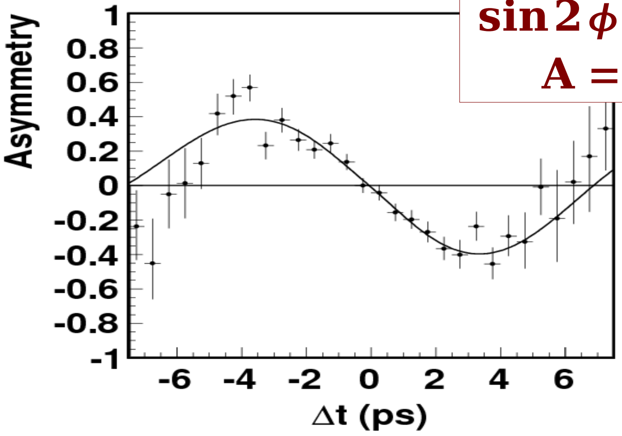


background subtracted
good tagged only

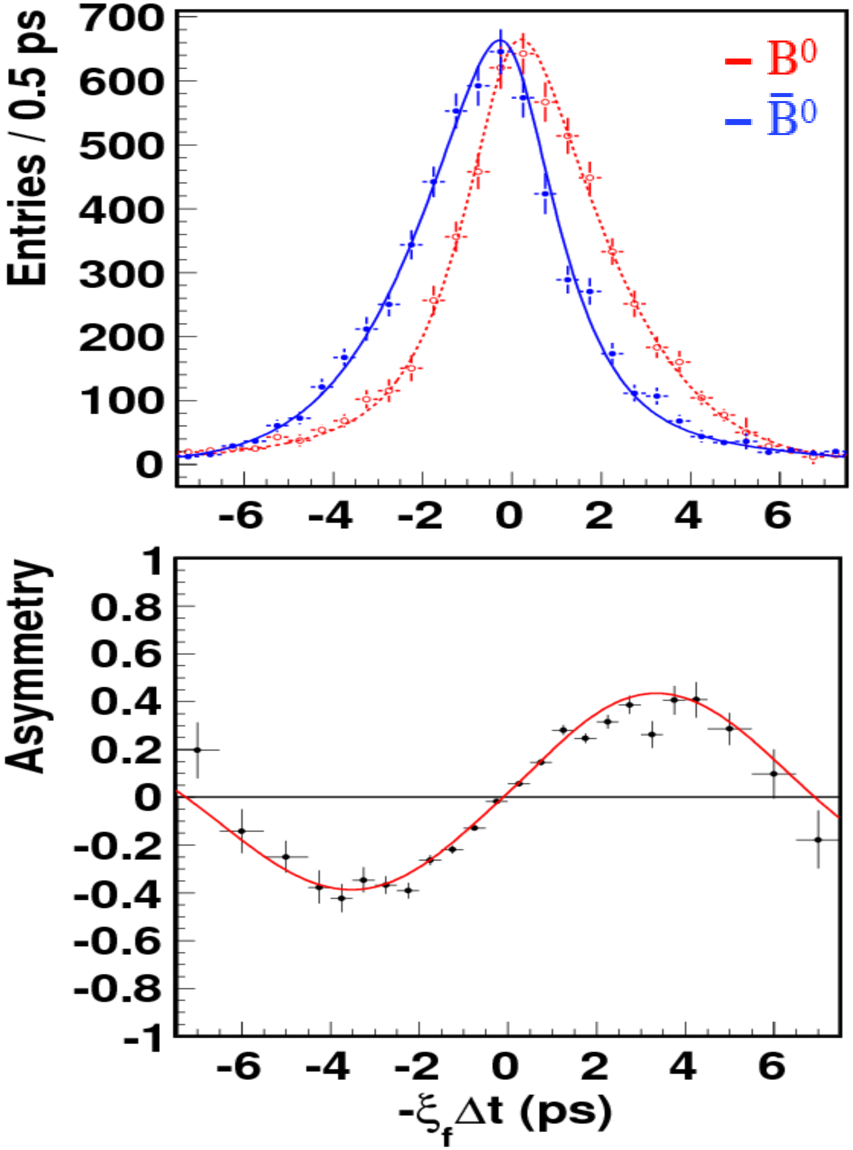
$\sin2\phi_1 = 0.671 \pm 0.029$
$A = -0.014 \pm 0.021$

$\sin2\phi_1 = 0.641 \pm 0.047$
$A = 0.019 \pm 0.026$





$\sin 2\phi_1$ in $(c\bar{c})K^0$ … **772×10^6 $B\bar{B}$ pairs**

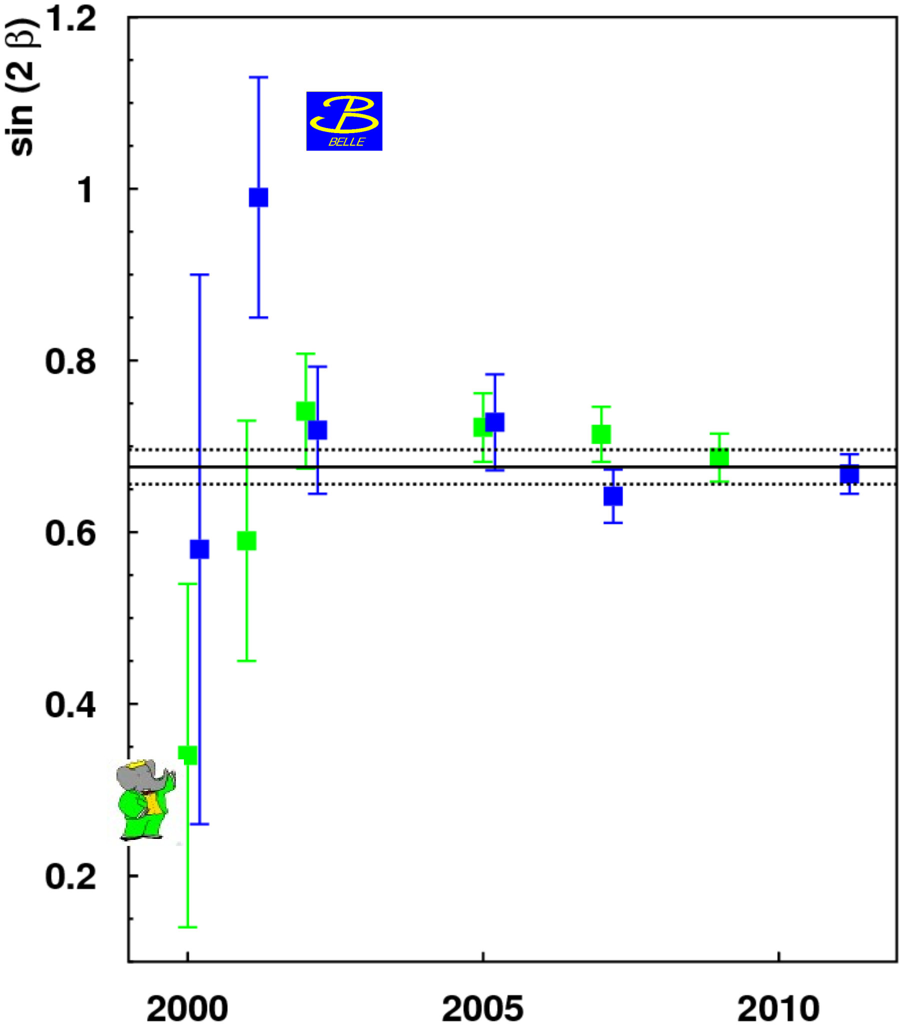


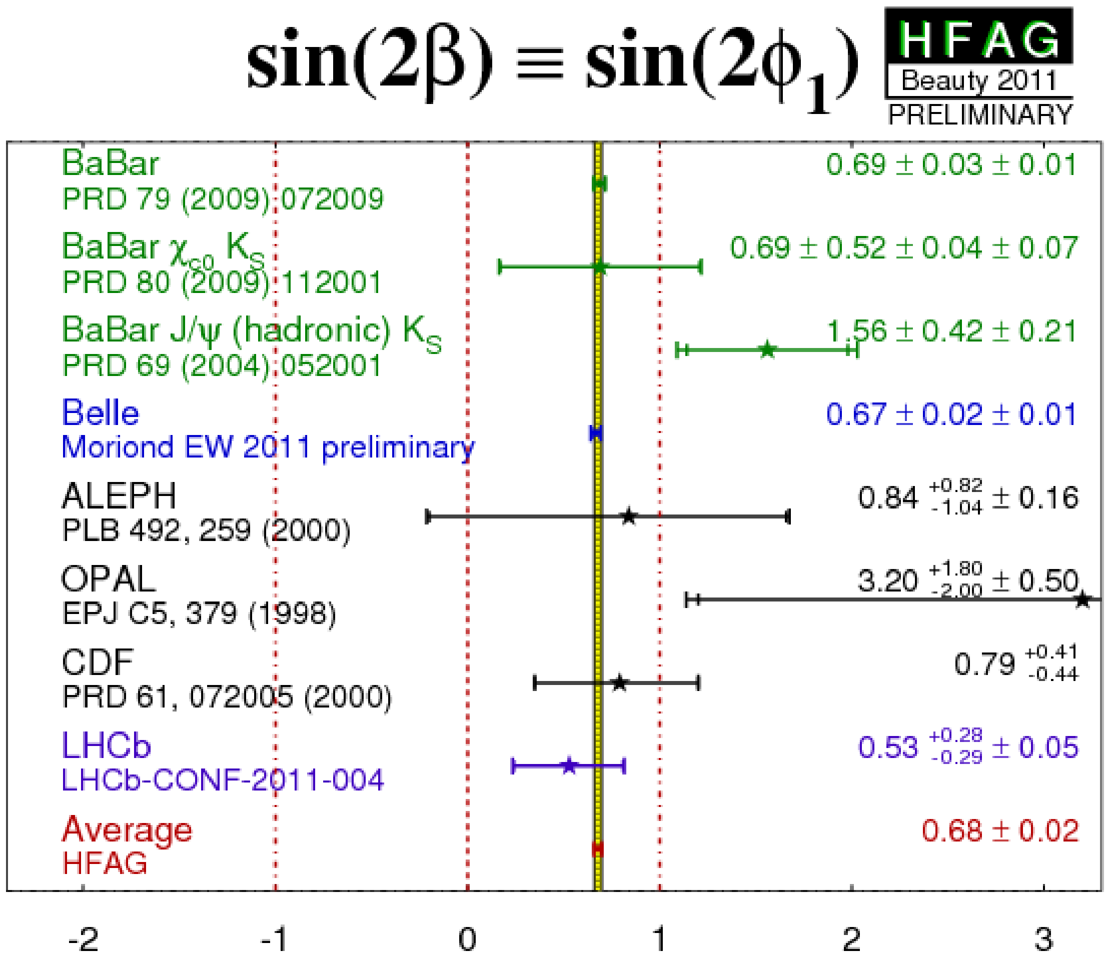
$$\sin 2\phi_1 = 0.668 \pm 0.023 \pm 0.013$$

$$A = 0.007 \pm 0.016 \pm 0.013$$

- ○ World's most precise measurements
- ○ anchor point of the SM
- ○ still statistically limited !

La raison d'être of the B factories



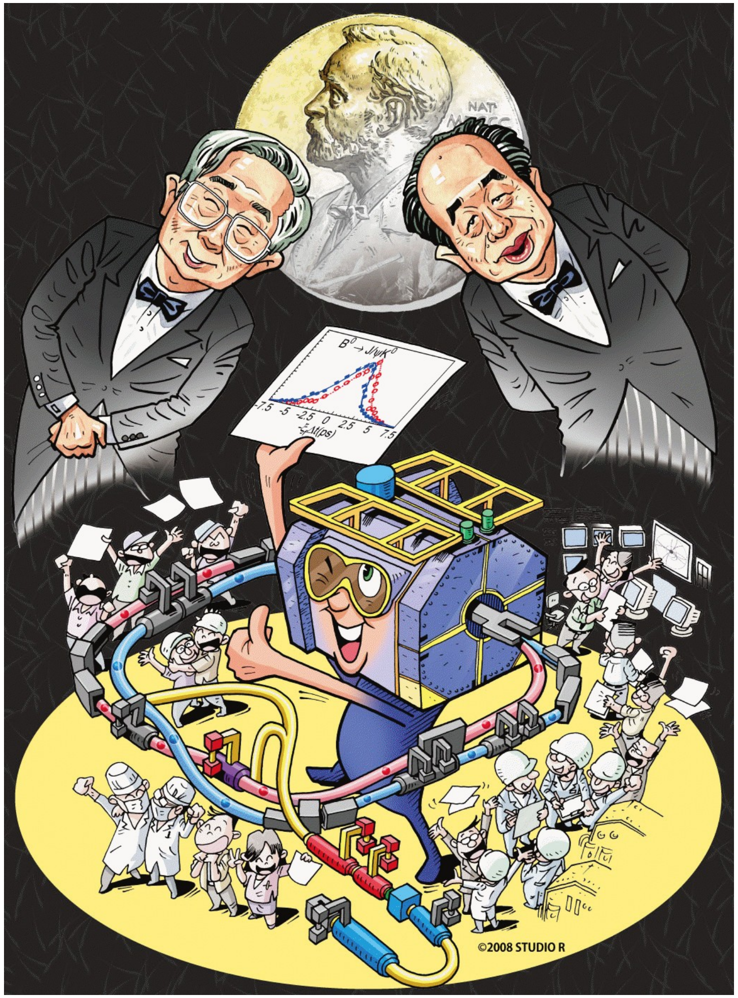


$$\boxed{\beta = (21.4 \pm 0.8)^\circ}$$

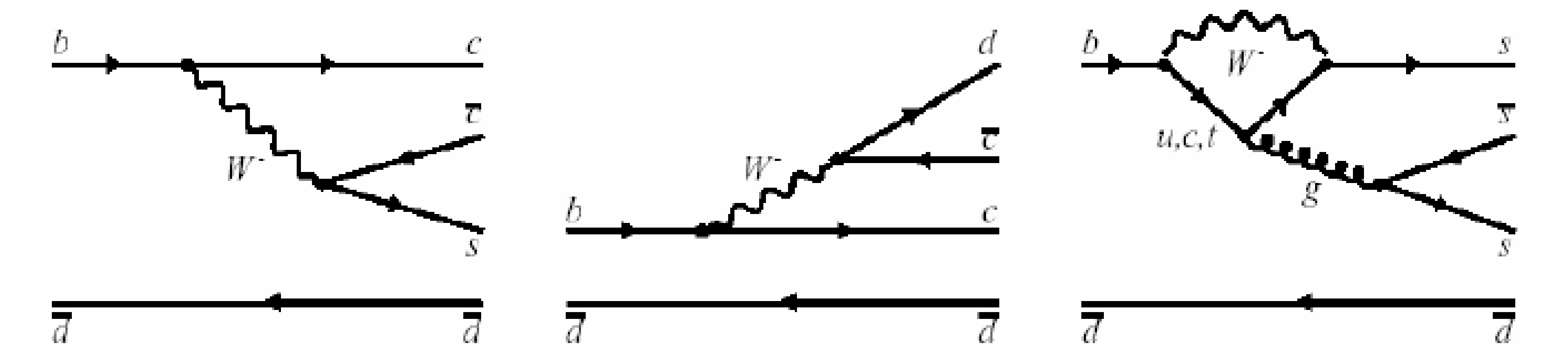
What is the source of CP violation ?
The Kobayashi-Maskawa phase is the source

Critical role of the B factories in the verification of the KM hypothesis

A single irreducible phase in the weak interaction matrix accounts for most of the CPV observed in kaons and B's



β in other modes



$J/\psi K^0_S, \psi(2S)K^0_S, \chi_{c1}K^0_S,$
$\eta_c K^0_S, J/\psi K^0_L,$
$J/\psi K^{*0}(K^{*0} \to K^0_S \pi^0)$

$D^{*+}D^-, D^+D^-$
$J/\psi \pi^0, D^{*+}D^{*-}$

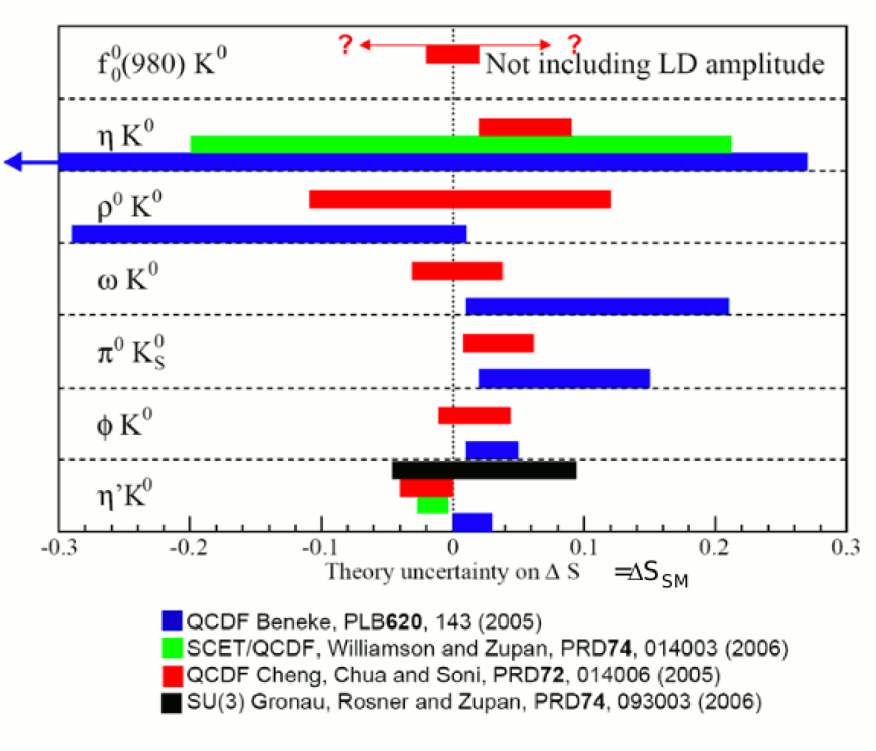
$\phi K^0, K^+K^-K^0_S,$
$K^0_S K^0_S K^0_S, \eta' K^0, K^0_S \pi^0,$
$\omega K^0_S, f_0(980)K^0_S$

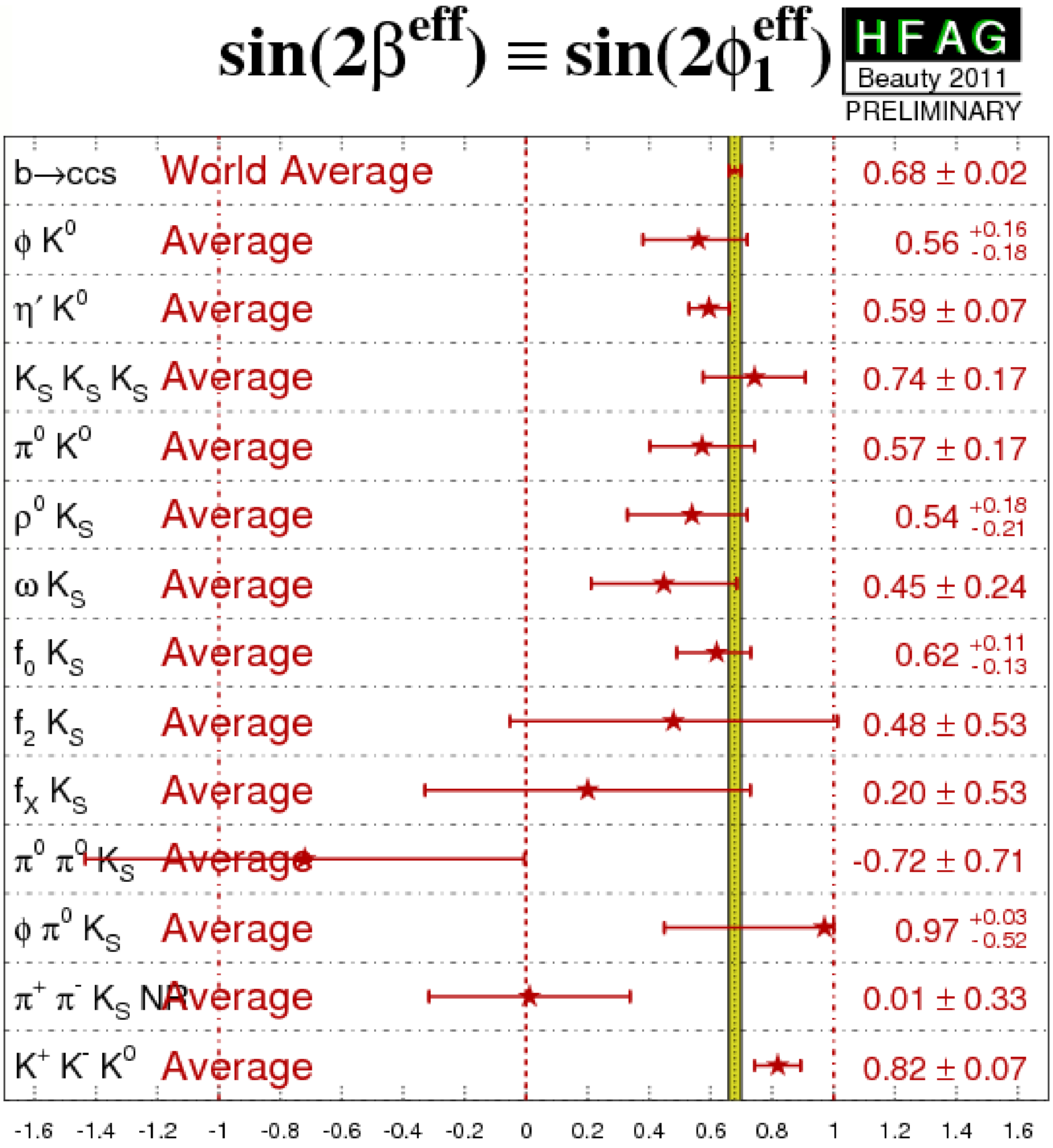
increasing tree diagram amplitude ←

increasing sensitivity to new physics →

possible new sources of CPV ?

β with b→s penguins





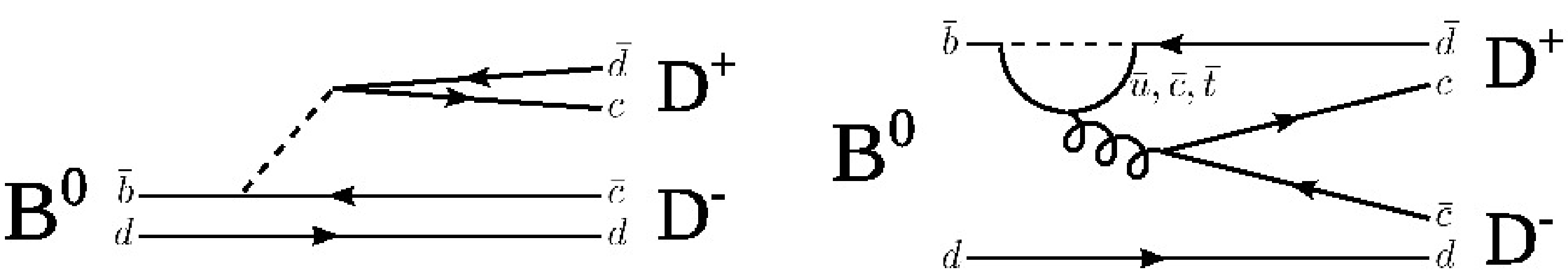
More statistics crucial
for mode-by-mode studies

Recent update of $B^0 \to D^+ D^-$ mode

772×10^6 $B\bar{B}$ pairs

preliminary

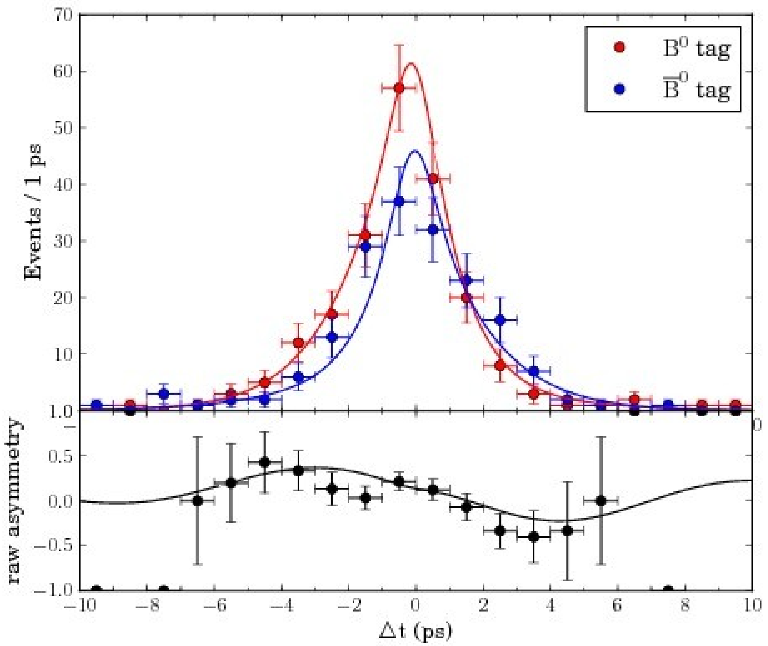
shown at EPS11

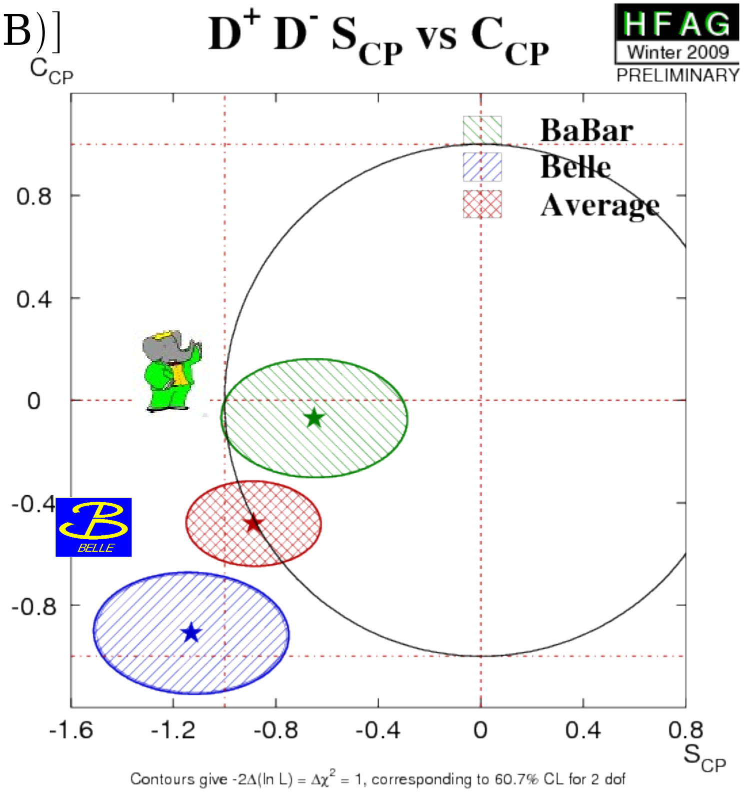


SM prediction: $S = -\sin 2\beta$ and $A = 0$ [Z.Z Xing, PRD61, 014010 (1999)]

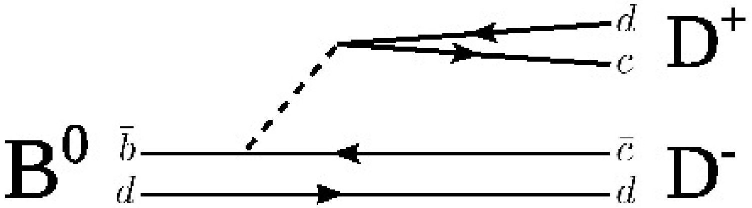
$$B^0 \to D^+ D^- \to (K^- \pi^+ \pi^+)(K^+ \pi^- \pi^-)$$
$$\to (K^- \pi^+ \pi^+)(K^0_S \pi^-)$$

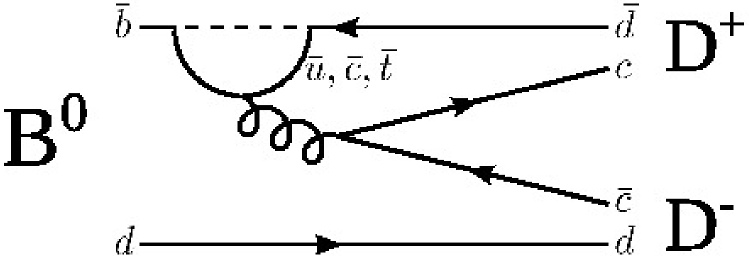
[> × 2 signal yield compared to previous analysis (535 MBB)]





Recent update of $B^0 \rightarrow D^+ D^-$ mode





772×10^6 $B\bar{B}$ pairs

preliminary shown at EPS11

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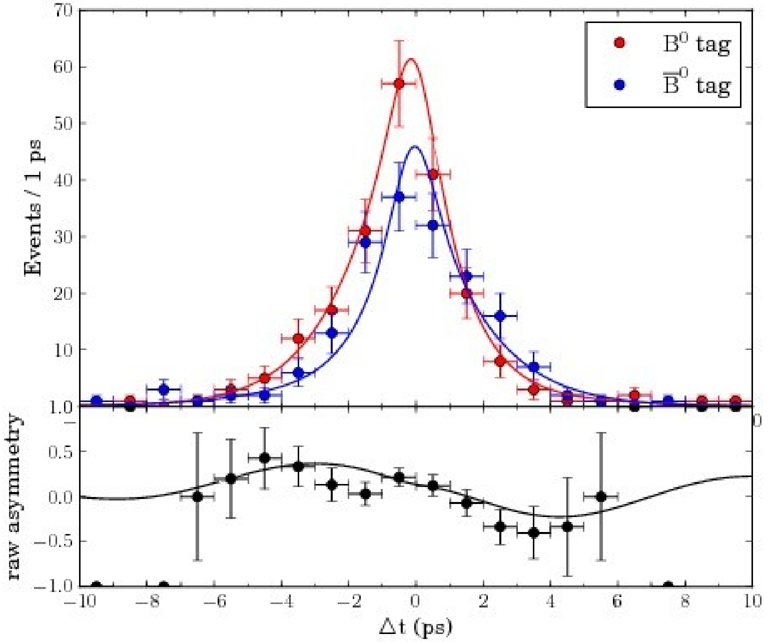
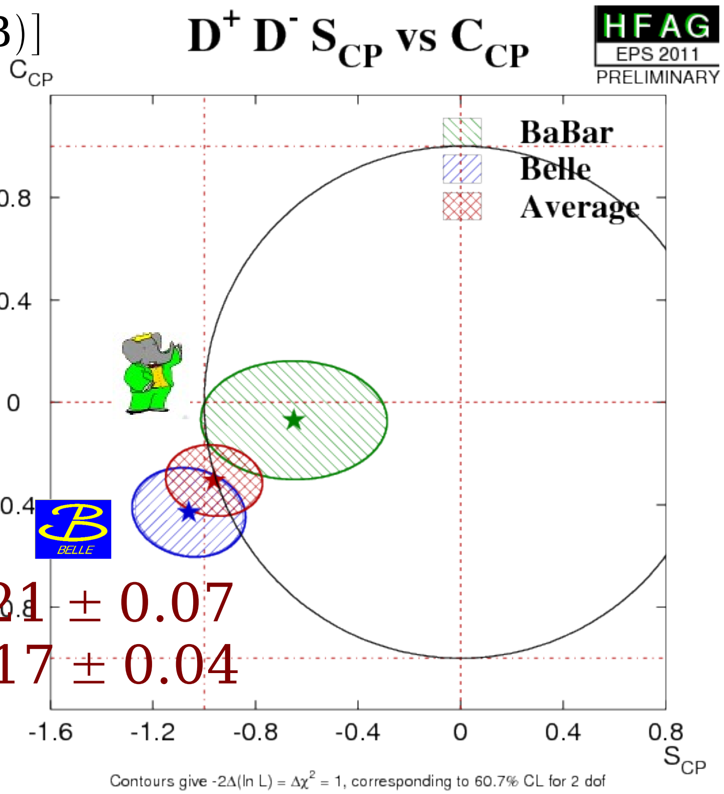
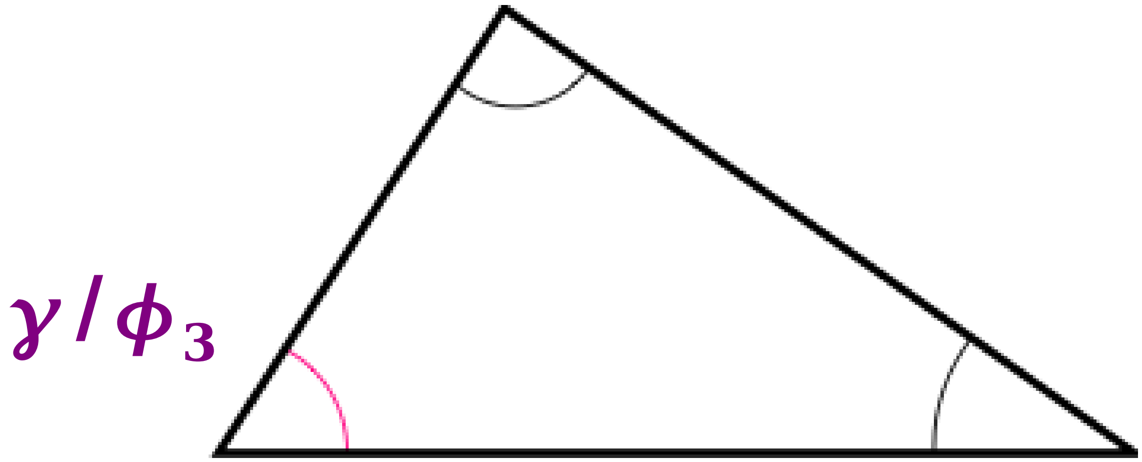




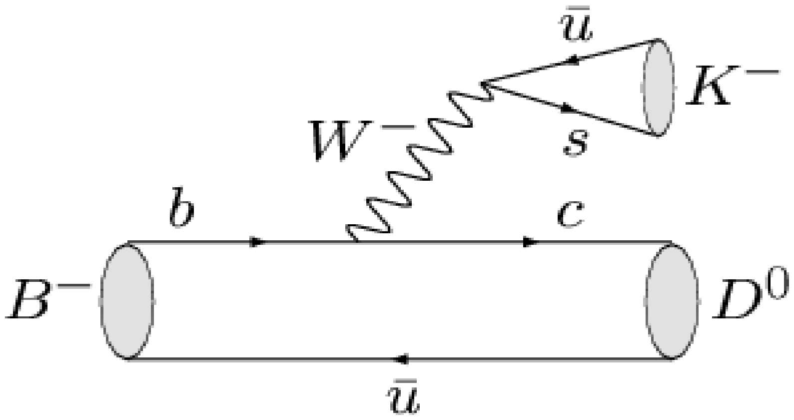
$$S = -1.06 \pm 0.21 \pm 0.07$$
$$A = +0.43 \pm 0.17 \pm 0.04$$

Measurement(s) of the CKM angle γ/ϕ_3 at Belle



γ measurements from $B^{\pm} \rightarrow DK^{\pm}$

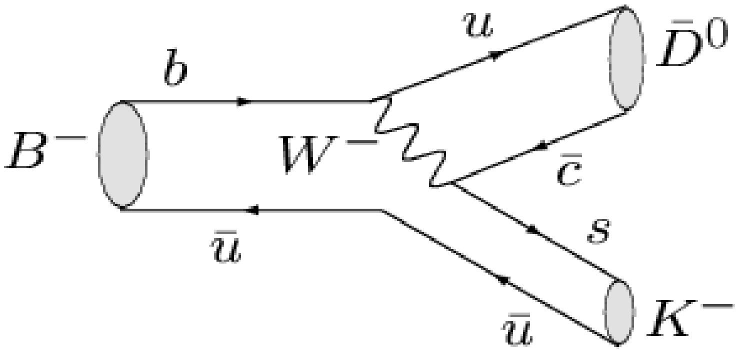
- ○ Theoretically pristine $B \rightarrow DK$ approach
- ○ Access γ via interference between $B^- \rightarrow D^0 K^-$ and $B^- \rightarrow \overline{D}^0 K^-$



color allowed

$B^- \rightarrow D^0 K^- \sim V_{cb} V_{us}^*$

$\sim \mathbf{A\lambda^3}$



color suppressed

$B^- \rightarrow \overline{D}^0 K^- \sim V_{ub} V_{cs}^*$

$\sim \mathbf{A\lambda^3(\rho - i\eta)}$

relative magnitude of suppressed amplitude is r_B

$$\boxed{r_B = \frac{|A_{\text{suppressed}}|}{|A_{\text{favoured}}|} \sim \frac{|V_{ub} V_{cs}^*|}{|V_{cb} V_{us}^*|} \times [\text{color supp}] = 0.1\text{-}0.2}$$

relative weak phase is γ, relative strong phase is δ_B

γ measurements from $B^{\pm} \to DK^{\pm}$

- Reconstruct D in final states accessible to both D^0 and $\overline{D}^0$
  - $D = D_{CP}$, CP eigenstates as K^+K^-, $\pi^+\pi^-$, $K_S\pi^0$

    GLW method (Gronau-London-Wyler)
  - $D = D_{sup}$, Doubly-Cabbibo suppressed decays as $K\pi$

    ADS method (Atwood-Dunietz-Soni)
  - Three-body decays as $D \to K_S\pi^+\pi^-$, $K_SK^+K^-$

    GGSZ (Dalitz) method (Giri-Grossman-Soffer-Zupan)

- Largest effects due to
  - charm mixing
  - charm CP violation

  } negligible

  Y.Grossman, A.Soffer, J.Zupan
  [PRD 72, 031501 (2005)]

- Different B decays (DK, D^*K, DK^*)
  - different hadronic factors (r_B, δ_B) for each

$B \rightarrow D^{(*)} K^{(*)}$ Dalitz analysis

Reconstruction of three−body final states D^0, $\overline{D}^0 \rightarrow K_S \pi^+ \pi^-$

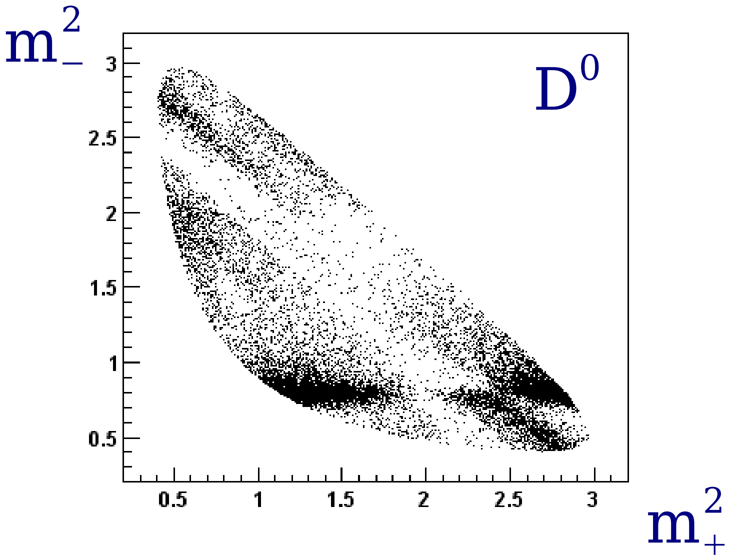
Amplitude for each Dalitz point is described as:

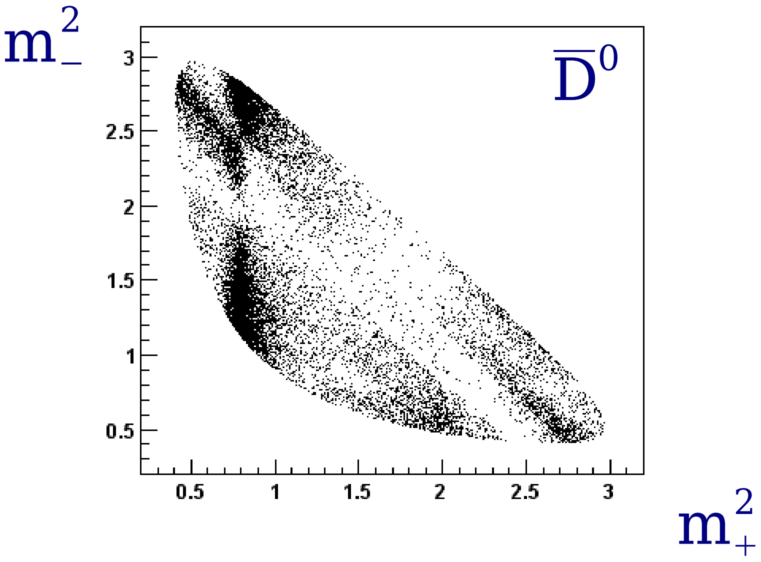
$$\overline{D}^0 \rightarrow K_S \pi^+ \pi^- \sim f(m_+^2, m_-^2)$$
$$D^0 \rightarrow K_S \pi^+ \pi^- \sim f(m_-^2, m_+^2)$$

model the amplitudes
(using tagged D sample)

$$B^+ \rightarrow (K_S \pi^+ \pi^-)_D K^+ : f(m_+^2, m_-^2) + r_B e^{i(\delta_B + \gamma)} f(m_-^2, m_+^2)$$

$m_- = M(K_S \pi^-)$
$m_+ = M(K_S \pi^+)$





$$B^- \rightarrow (K_S \pi^+ \pi^-)_D K^- : f(m_-^2, m_+^2) + r_B e^{i(\delta_B - \gamma)} f(m_+^2, m_-^2)$$

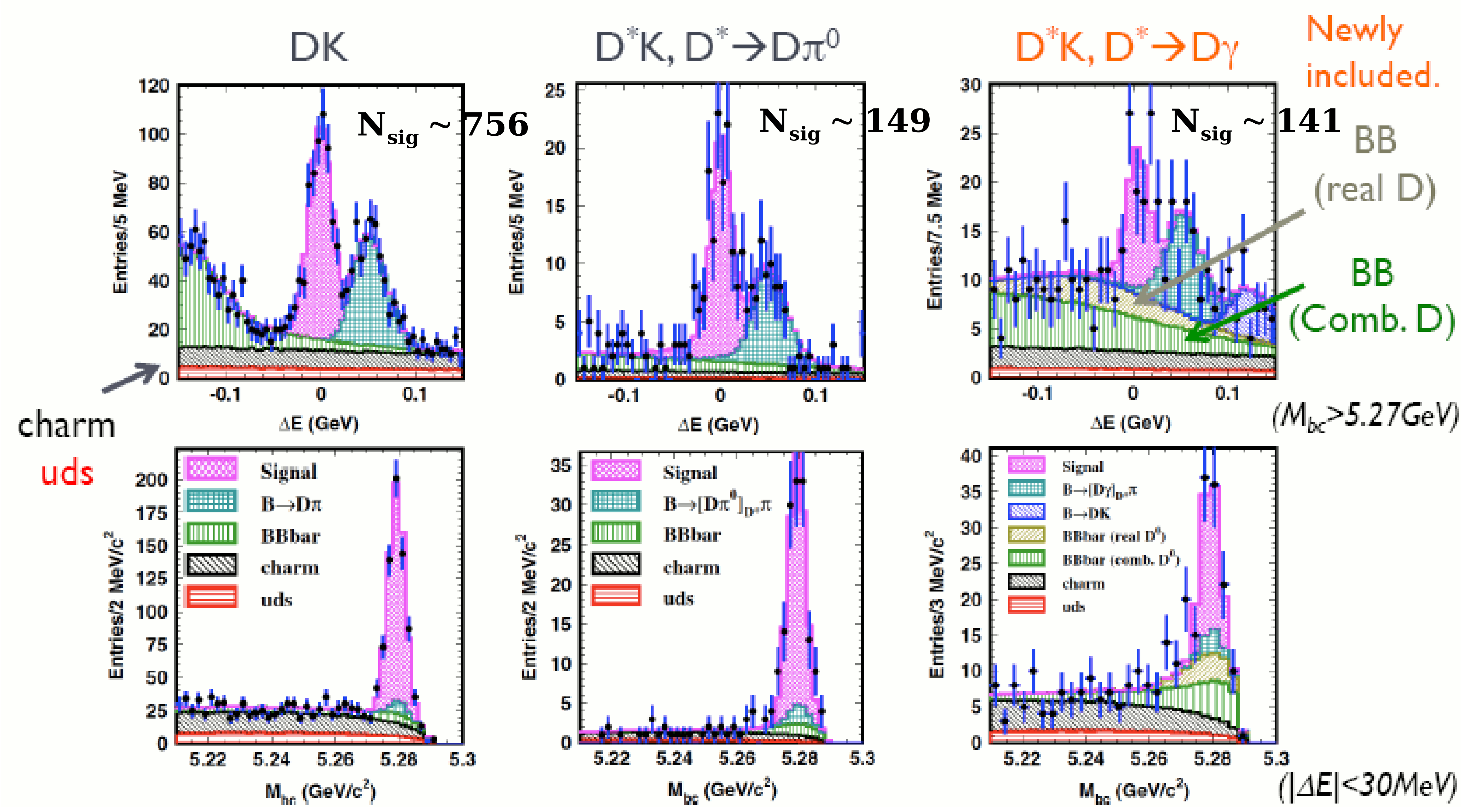
Simultaneous fit of B^+ and B^- to extract parameters r_B, γ and δ_B

Note: 2 fold ambiguity on γ: $(\gamma, \delta_B) \rightarrow (\gamma + \pi, \delta_B + \pi)$

$B^- \to D^{(*)}(K_S\pi\pi)K^-$ Dalitz, ΔE and M_{bc} projections

$|\cos\theta_{thr}| < 0.8$ and $F > -0.7$

PRD 81, 112002 (2010)
657×10^6 $B\overline{B}$ pairs



$N_{sig} \sim 756$

$N_{sig} \sim 149$

$N_{sig} \sim 141$

Newly included.

BB (real D)

BB (Comb. D)

charm

uds

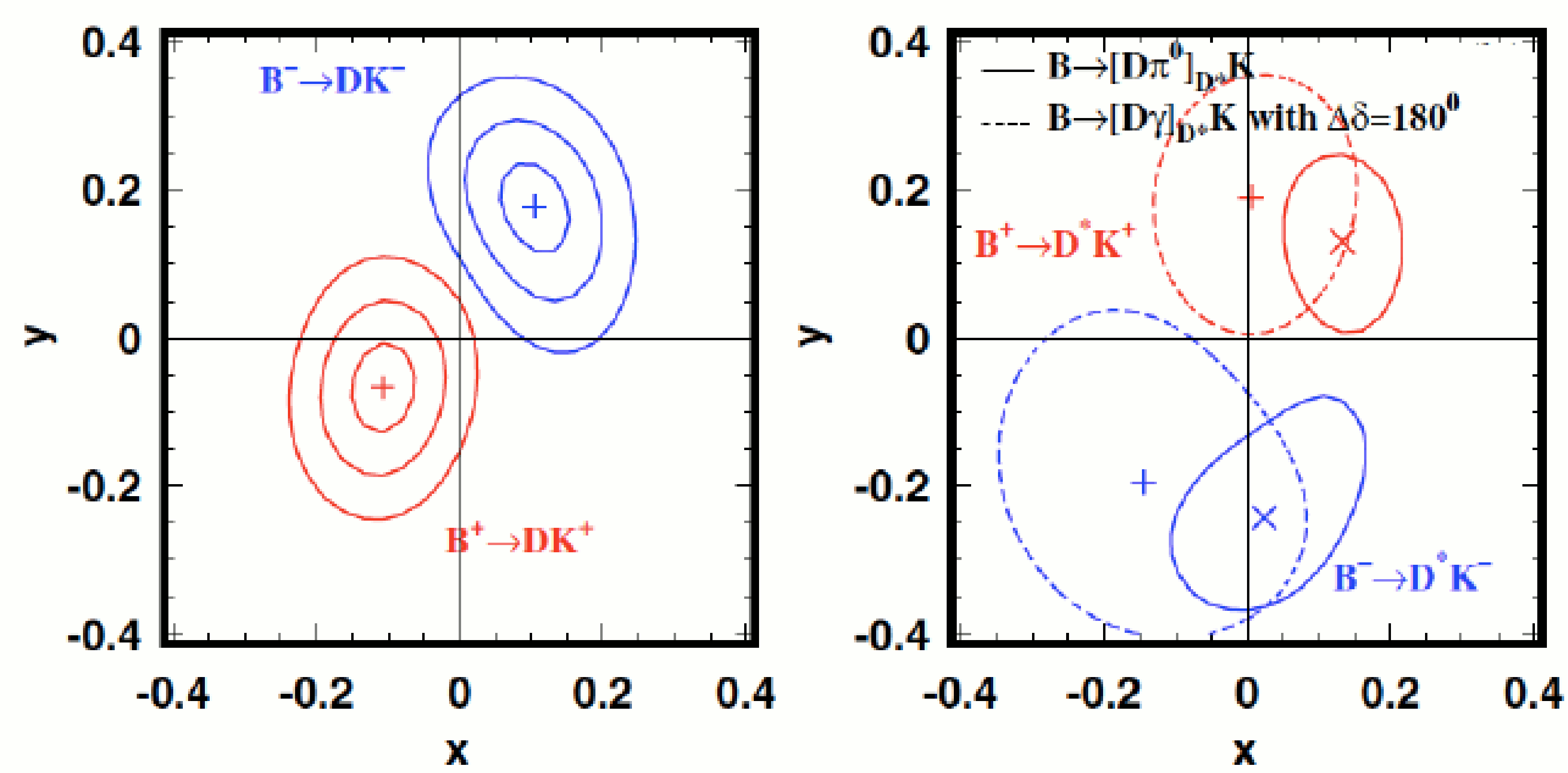
(M_{bc}>5.27GeV)

($|\Delta E|$<30MeV)

γ measurement with $B \to D(K_S \pi\pi)K$

PRD 81, 112002 (2010)
657×10^6 $B\bar{B}$ pairs

$$x_\pm = r_B \cos(\delta_B \pm \gamma), \quad y_\pm = r_B \sin(\delta_B \pm \gamma)$$



$$\gamma = (80.8\,^{+13.1}_{-14.8} \pm 5.0 \pm 8.9)^\circ$$
$$r_B = 0.161\,^{+0.040}_{-0.038} \pm 0.011\,^{+0.050}_{-0.010}$$
$$\delta_B = (137.4\,^{+13.0}_{-15.7} \pm 4.0 \pm 22.9)^\circ$$

$$\gamma = (73.9\,^{+18.9}_{-20.2} \pm 4.2 \pm 8.9)^\circ$$
$$r_B = 0.196\,^{+0.073}_{-0.072} \pm 0.013\,^{+0.062}_{-0.012}$$
$$\delta_B = (341.7\,^{+18.6}_{-20.9} \pm 3.2 \pm 22.9)^\circ$$

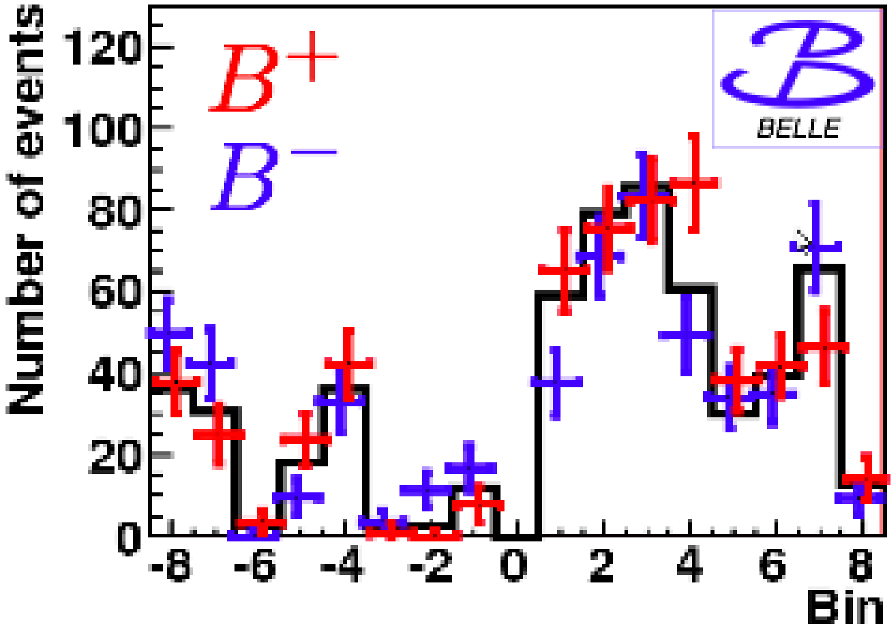
combining both B modes (Dalitz): $\boldsymbol{\gamma = (78.4\,^{+10.8}_{-11.6} \pm 3.6 \pm 8.9)^\circ}$

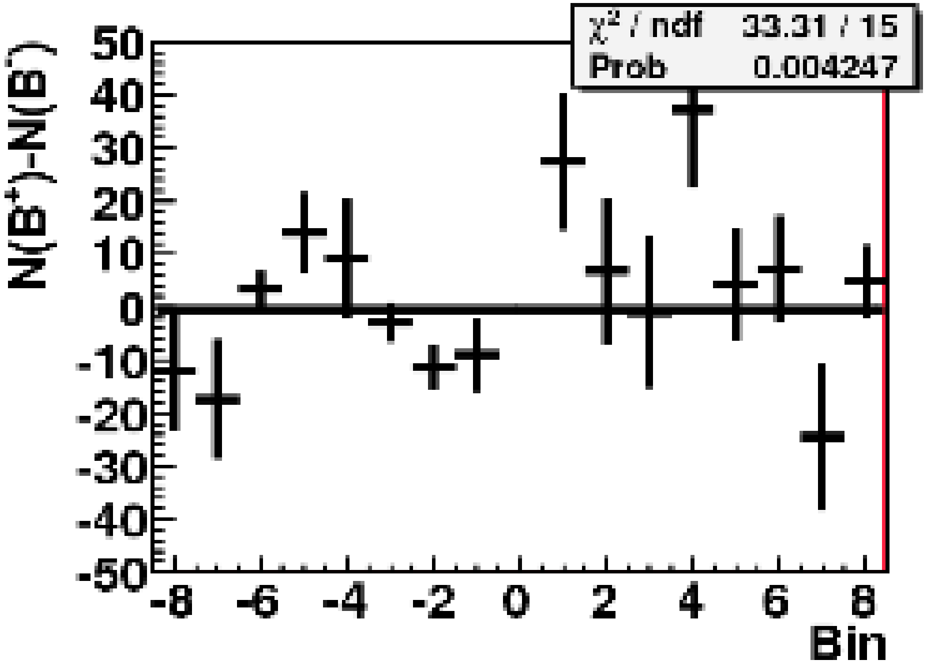
CPV significance is 3.5 standard deviations

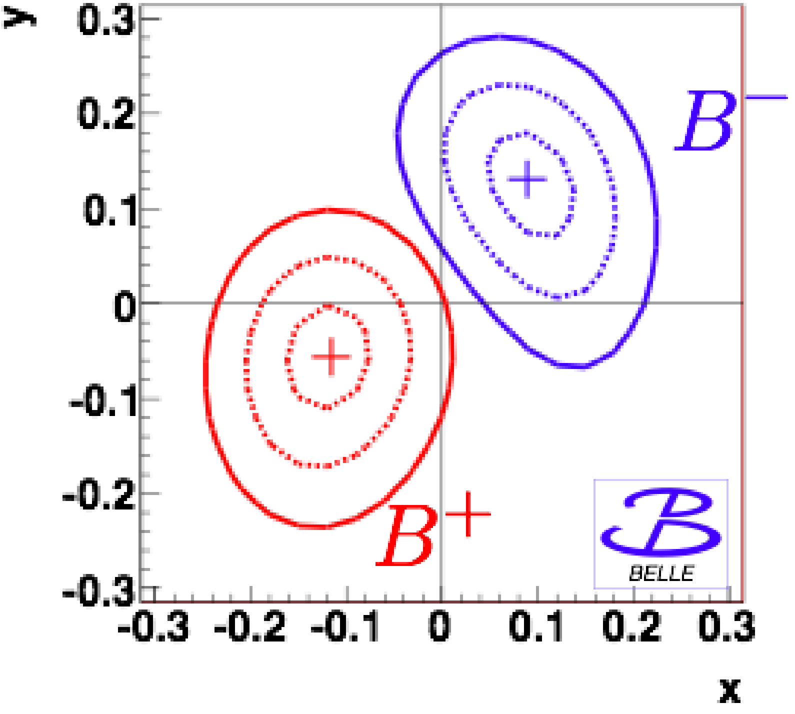
(model-dependent error will limit viability of this approach)

Binned Dalitz method result in B → DK from 772 million events

arXiv:1106.4046







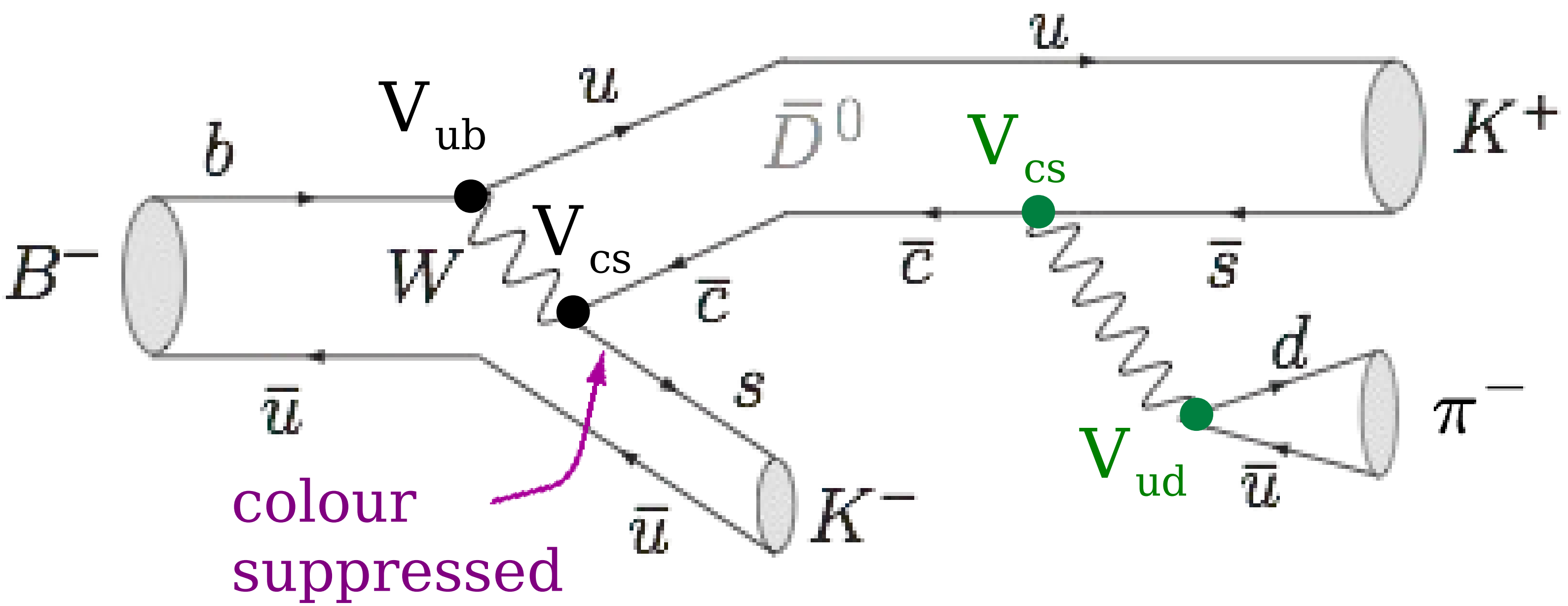
$$\gamma = (77.3 \, {}^{+15.1}_{-14.9} \pm 4.2 \pm 4.3)^\circ$$

$$r_B = 0.145 \pm 0.030 \pm 0.011 \pm 0.011$$

$$\delta_B = (129.9 \pm 15.0 \pm 3.9 \pm 4.7)^\circ$$

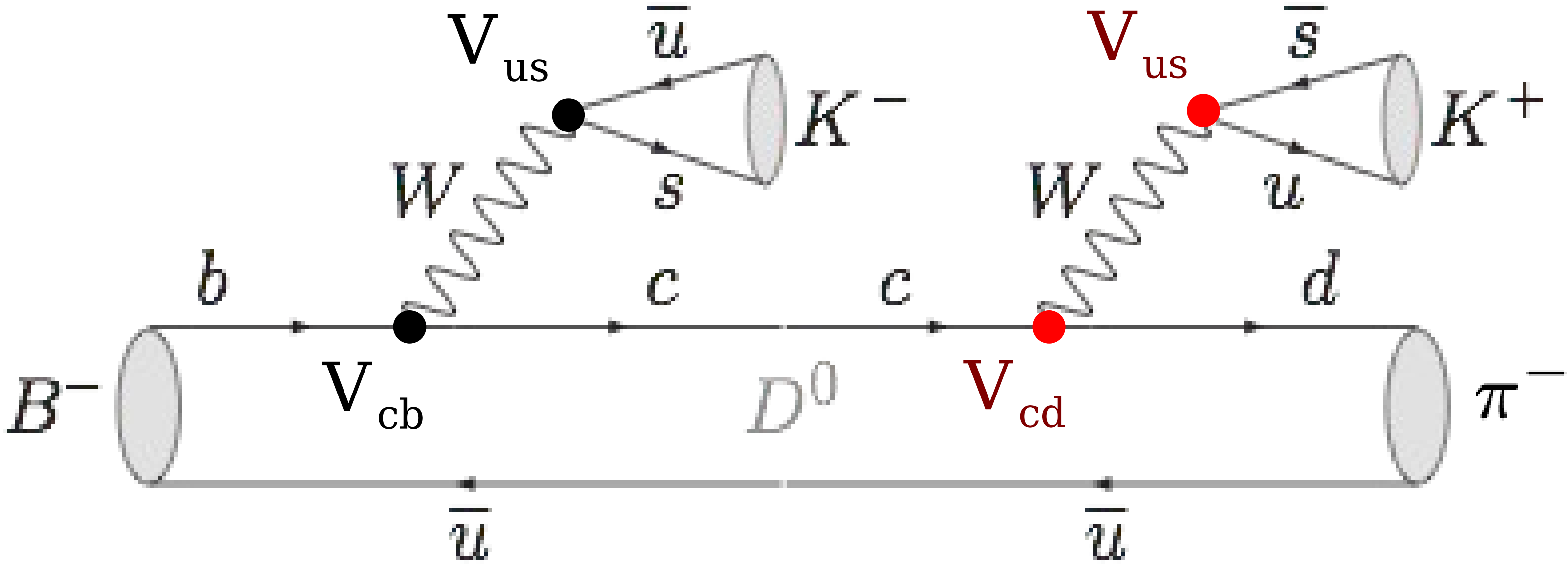
uncertainty in c_i, s_i
from CLEO data
(can reduce using
future BES-III data)

ADS method measures ϕ_3 via the interference in rare $B^- \to [K^+ \pi^-]_D K^-$ decays



colour suppressed

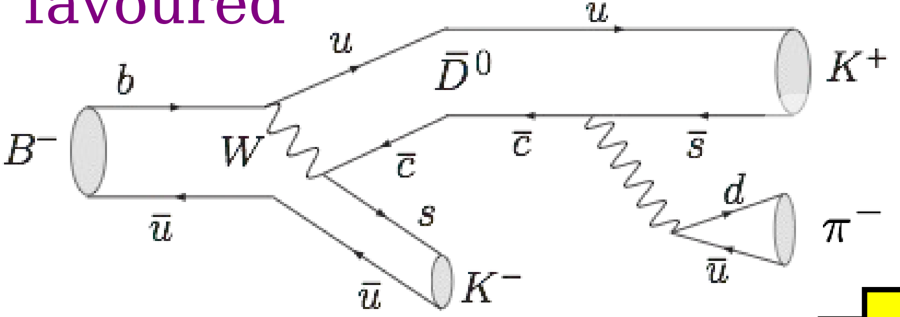
Cabibbo favoured D decay



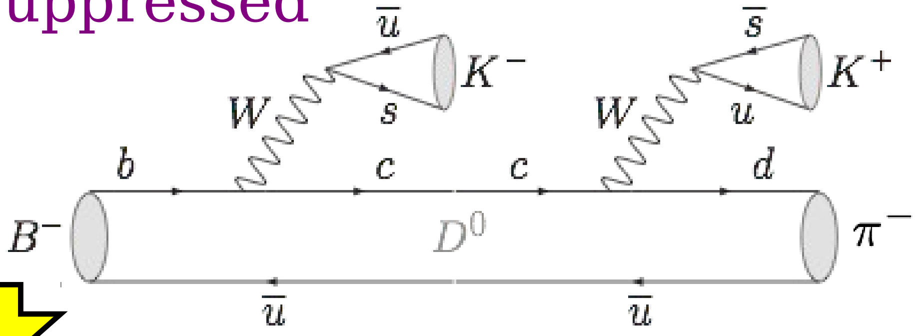
doubly Cabibbo suppressed D decay

ADS rate and asymmetry (relative to the common decay):

favoured

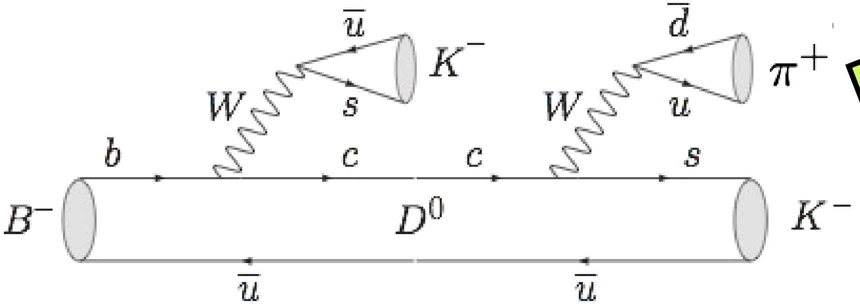


suppressed



$$\mathcal{R}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) + \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

common



$$= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos \phi_3$$

$$\mathcal{A}_{DK} = \frac{\Gamma([K^+\pi^-]\,K^-) - \Gamma([K^-\pi^+]\,K^+)}{\Gamma([K^-\pi^+]\,K^-) + \Gamma([K^+\pi^-]\,K^+)}$$

$$= 2\, r_B r_D \sin(\delta_B + \delta_D) \sin \phi_3 \,/\, \mathcal{R}_{DK}$$

where $r_D = \left| \frac{\mathcal{A}(D^0 \to K^+\pi^-)}{\mathcal{A}(\bar{D}^0 \to K^+\pi^-)} \right| = 0.0613 \pm 0.0010$

Yields for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events

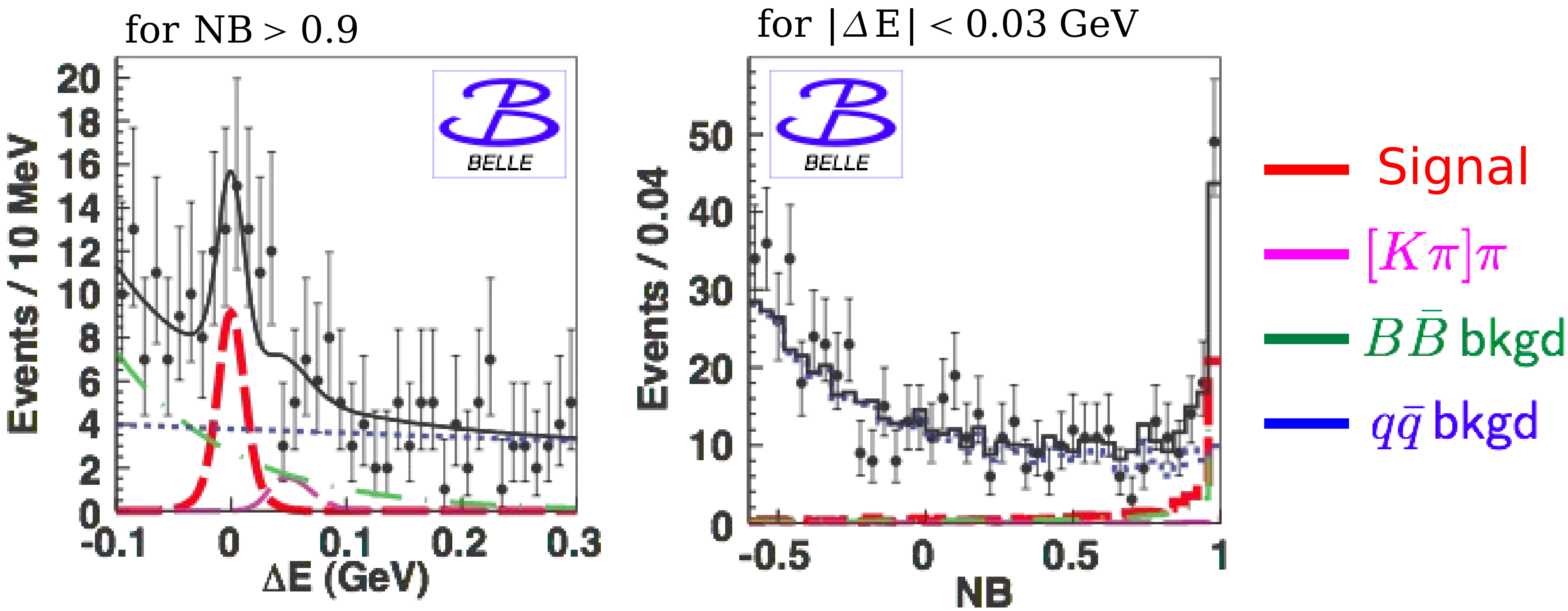
PRL 106, 231803 (2011)

Main background is $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) continuum

⇒ 10 variables combined to obtain a single NN output (NB)

(for example, at 99% bckg rej. signal eff. = 42% now becomes 60%)

Fit ΔE and NB distributions together to extract signal


for NB > 0.9

for $|\Delta E| < 0.03$ GeV

$56.0^{+15.1}_{-14.2}$ events

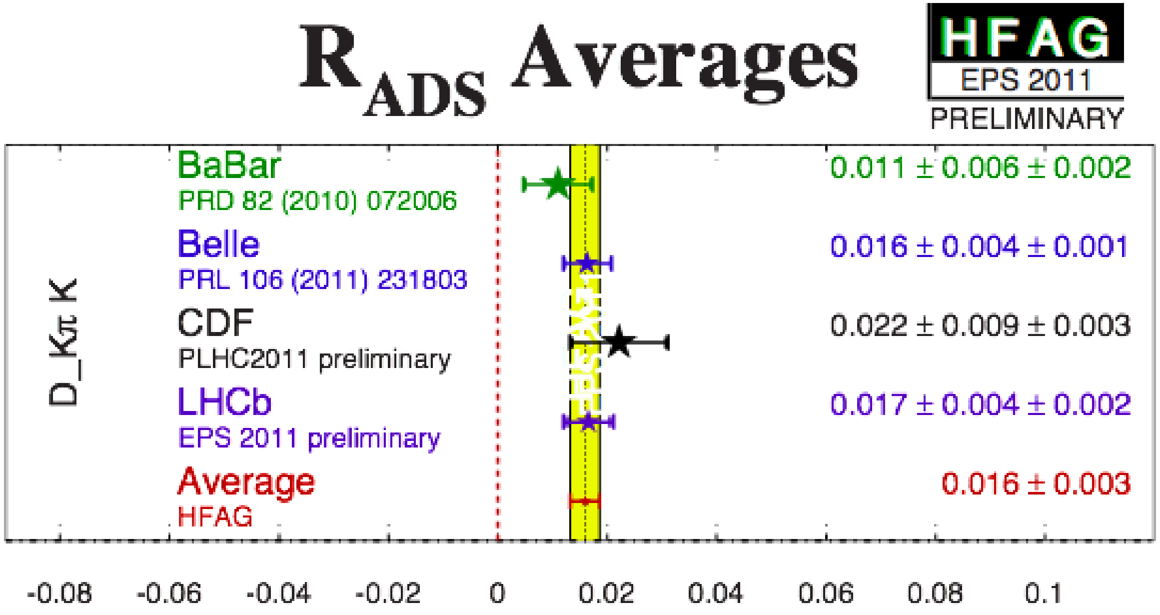
$R_{DK} = (1.63\,^{+0.44}_{-0.41}\,^{+0.07}_{-0.13}) \times 10^{-2}$

$A_{DK} = -0.39\,^{+0.26}_{-0.28}\,^{+0.04}_{-0.03}$

First evidence obtained with a significance of 3.8σ (including syst.)

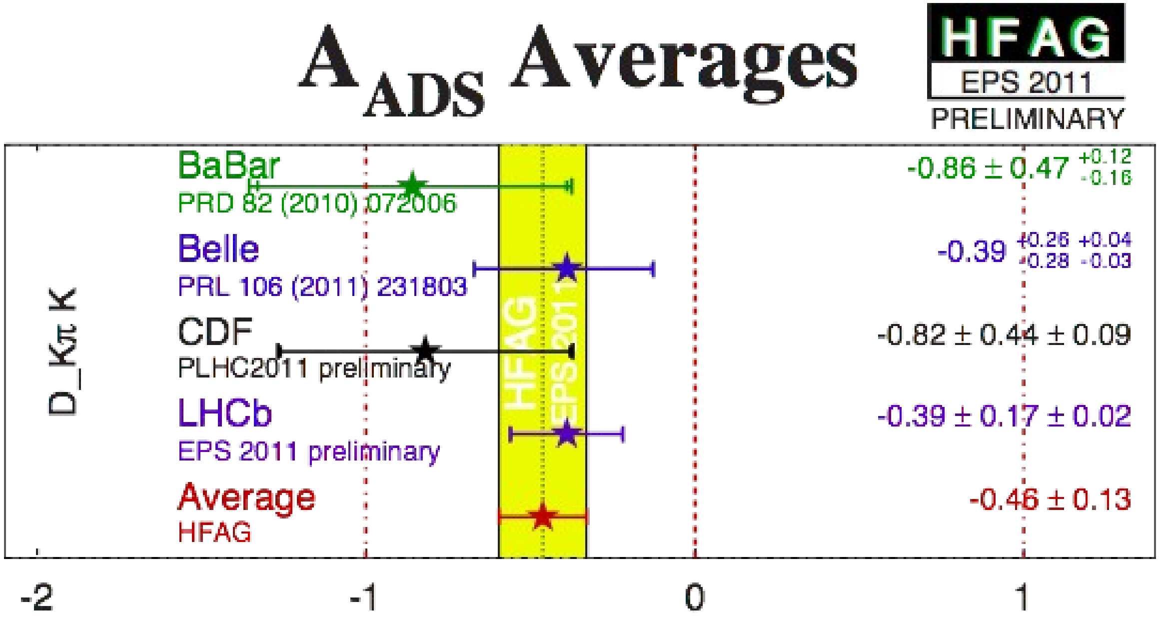
Results for the ADS mode $B^- \to [K^+\pi^-]_D K^-$ from 772 million $B\bar{B}$ events

PRL 106, 231803 (2011)



◀ $(1.63\,^{+0.44}_{-0.41}\,^{+0.07}_{-0.13}) \times 10^{-2}$

$\Rightarrow \; r_B \neq 0$



◀ $-0.39\,^{+0.26}_{-0.28}\,^{+0.04}_{-0.03}$

First evidence for the ADS mode $B^- \to [K^+\pi^-]_{D^*}K^-$ from Belle 772 million $B\bar{B}$ events

Preliminary
LP 2011

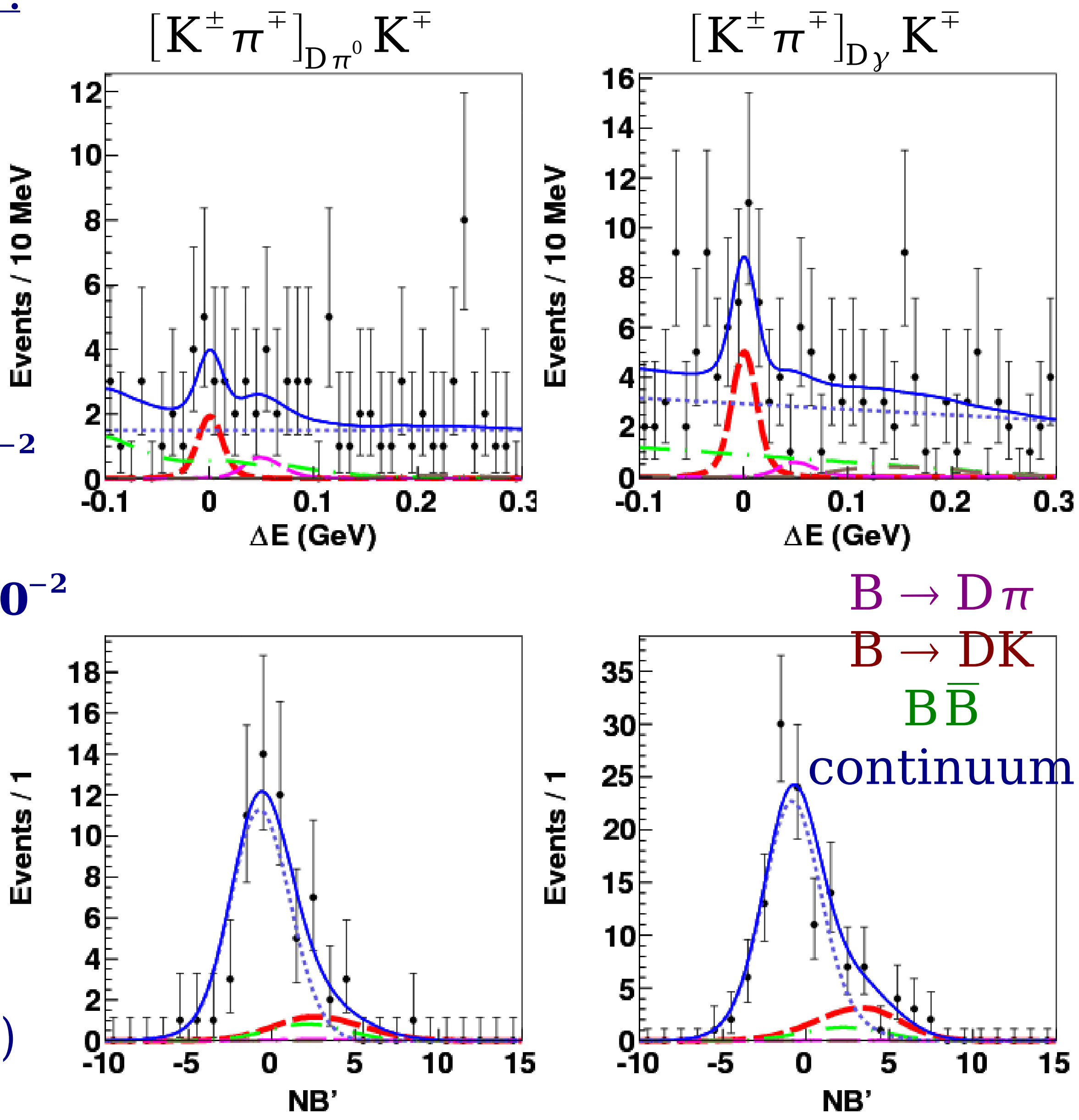
study both modes: $D^* \to D\pi^0$, $D\gamma$:

Signal seen
with a significance of 3.5σ
for $D^* \to D\gamma$ mode

Ratio to favored mode:

$$R_{D\pi^0} = (1.0\,^{+0.8}_{-0.7}(\text{stat})\,^{+0.1}_{-0.2}(\text{syst})) \times 10^{-2}$$

$$R_{D\gamma} = (3.6\,^{+1.4}_{-1.2}(\text{stat}) \pm 0.2(\text{syst})) \times 10^{-2}$$



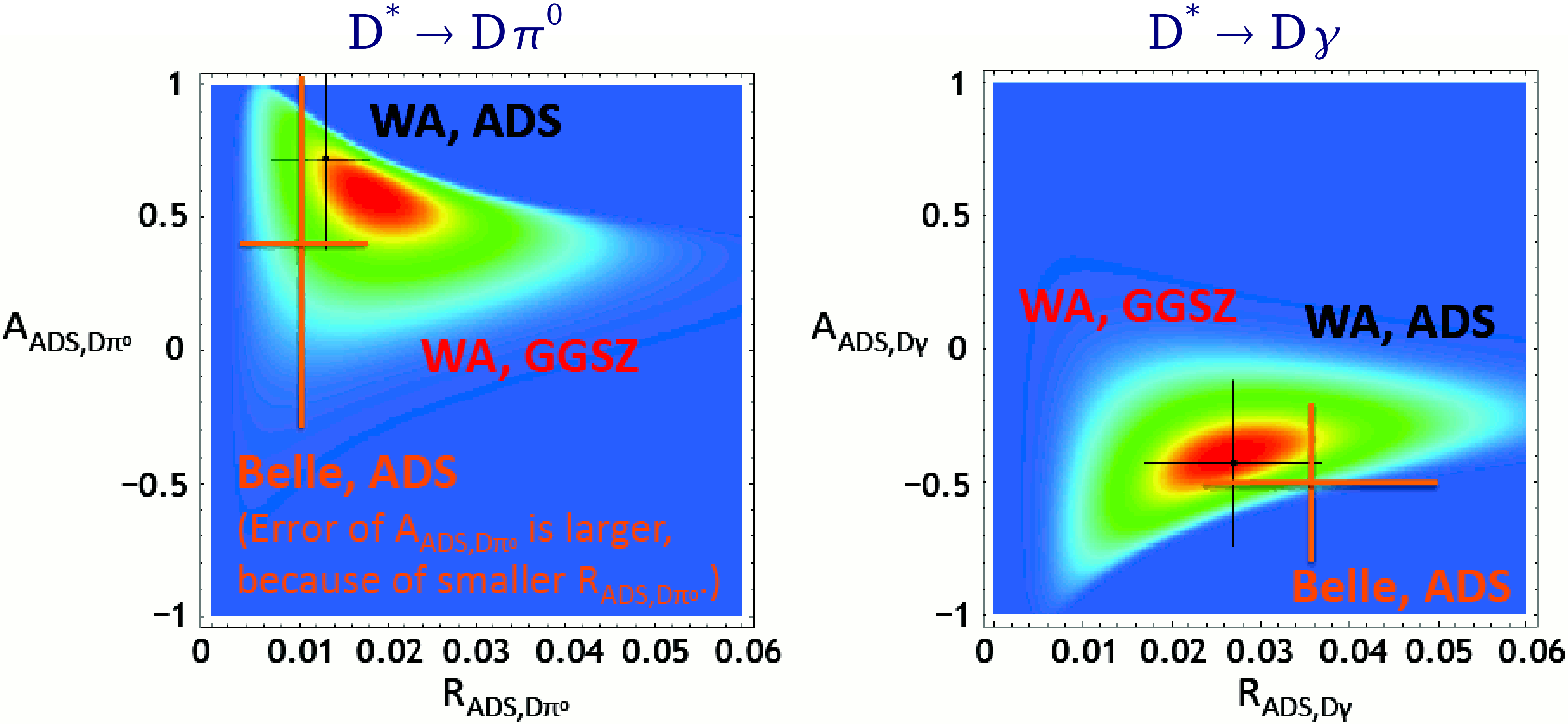
asymmetry:

$$A_{D\pi^0} = 0.4\,^{+1.1}_{-0.7}(\text{stat})\,^{+0.2}_{-0.1}(\text{syst})$$

$$A_{D\gamma} = -0.51\,^{+0.33}_{-0.29}(\text{stat}) \pm 0.08(\text{syst})$$

Comparison of the results obtained for $D^{*}K$ with expectations

(where ''expectations'' are derived from the GGSZ observables)



WA taken from HFAG 2011 summer.

GLW with $D_{CP}K$

D decays to CP eigenstates

Relation between $(A_{CP+}, A_{CP-}, R_{CP+}, R_{CP-})$ and (γ, r_B, δ_B)

$$R_{CP\pm} \simeq \frac{R_{D_{CP\pm}}}{R_{D_{fav}}}$$

$$A_{CP+} = \frac{2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma} \qquad A_{CP-} = \frac{-2 r_B \sin\delta_B \sin\gamma}{1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma}$$

$$R_{CP+} = 1 + r_B^2 + 2 r_B \cos\delta_B \cos\gamma \qquad R_{CP-} = 1 + r_B^2 - 2 r_B \cos\delta_B \cos\gamma$$

$\Rightarrow$ look for $R_{CP\pm} \neq 1$ and $A_{CP\pm} \neq 0$

$B \to Dh$, $D \to K\pi$ → $R_{D_{fav}}$

data (772 M$B\bar{B}$)

$B \to D\pi$

$B \to DK$

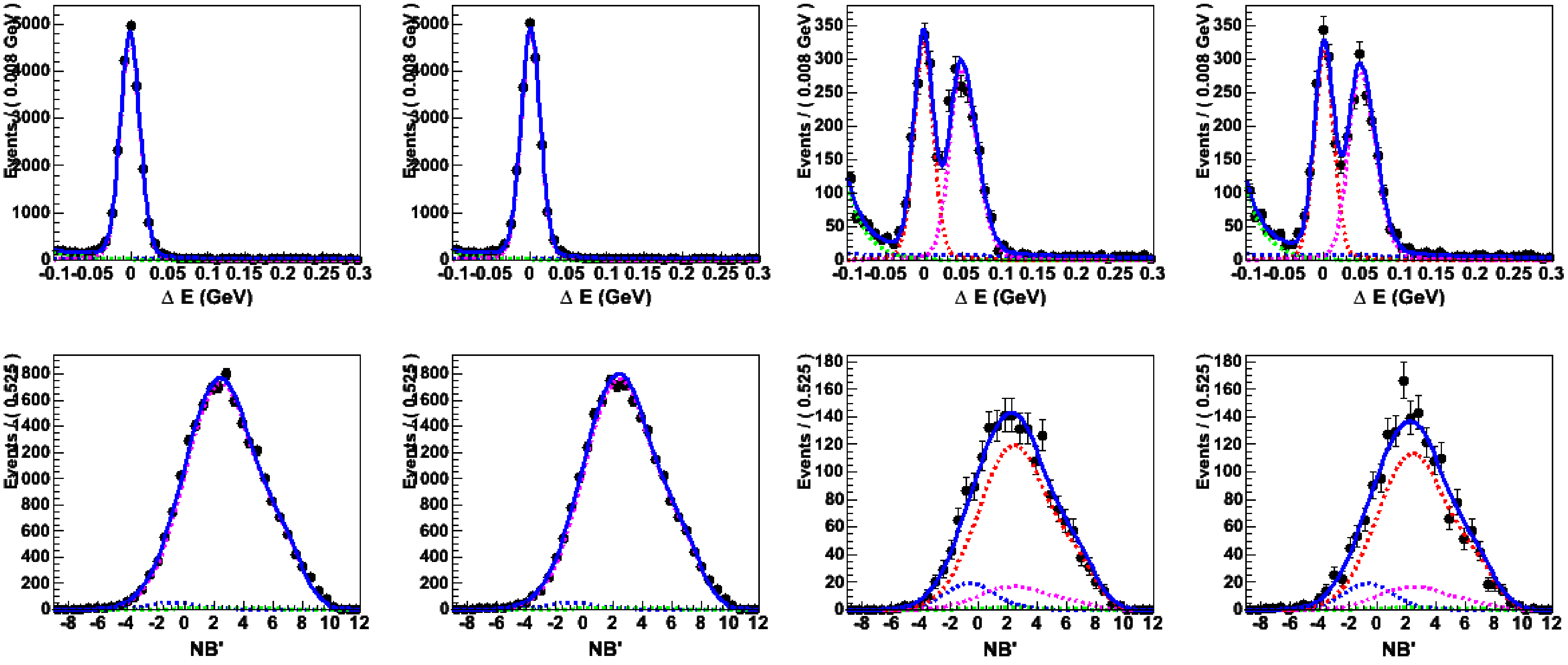
$B\bar{B}$

continuum

h is a pion candidate (KID<0.6)

h is a kaon candidate (KID>0.6)

$B^- \to Dh^-$ $B^+ \to Dh^+$ $B^- \to Dh^-$ $B^+ \to Dh^+$



⇒ $R_{D_{fav}} = (7.32 \pm 0.16)\%$, $A(DK) = (1.4 \pm 2.0)\%$

$B \to Dh,\ D \to K\pi \ \to \ R_+$

data (772 M$B\bar{B}$)

$B \to D\pi$

$B \to DK$

$B\bar{B}$

continuum

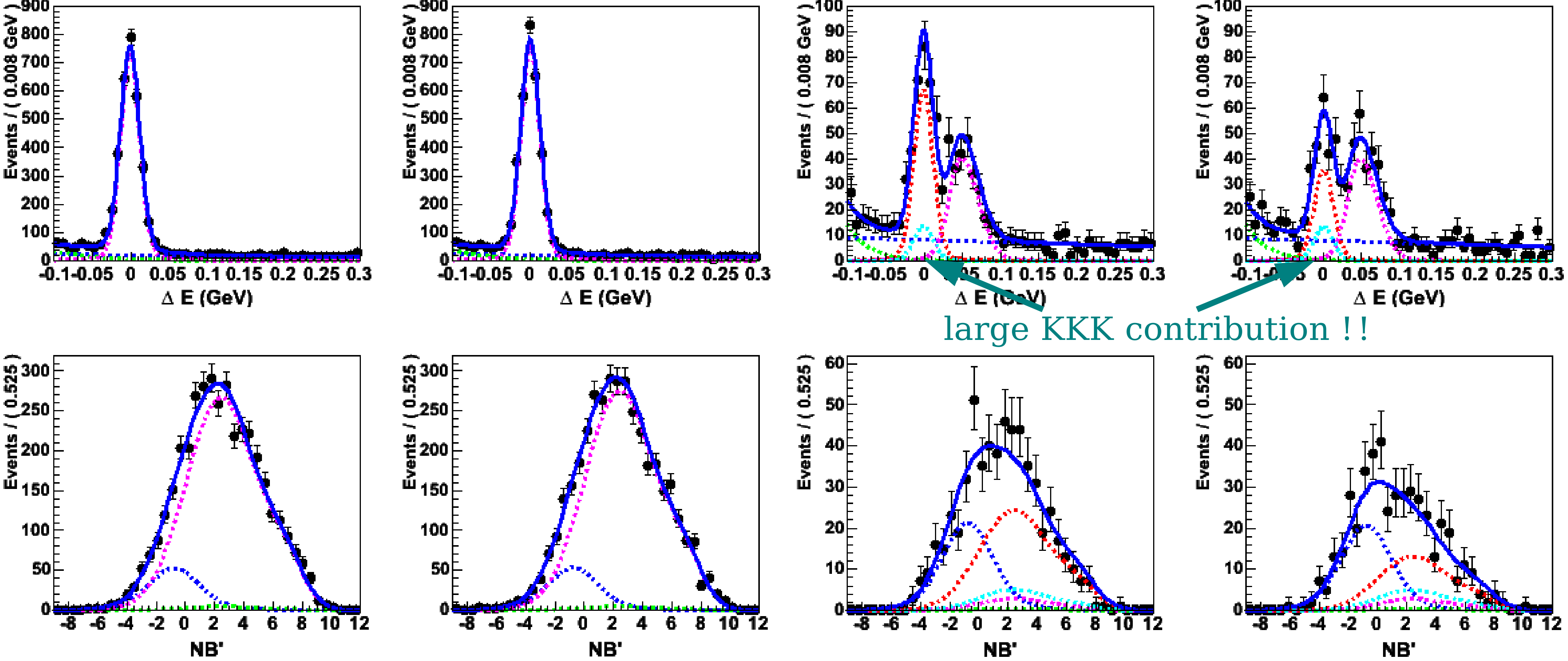
$D \to K^+K^-,\ \pi^+\pi^-$

Preliminary

LP 2011

h is a pion candidate (KID<0.6) h is a kaon candidate (KID>0.6)

$B^- \to Dh^-$ $B^+ \to Dh^+$ $B^- \to Dh^-$ $B^+ \to Dh^+$



large KKK contribution !!

$$\Rightarrow \ R_{D_{CP+}} = (7.56 \pm 0.51)\%,\ \ A_{D_{CP+}} = (28.7 \pm 6.0)\%$$

large asymmetry !!

$\mathbf{B \to Dh, D \to K\pi \;\to\; R_-}$

data $(772\ \mathrm{M}B\bar{B})$

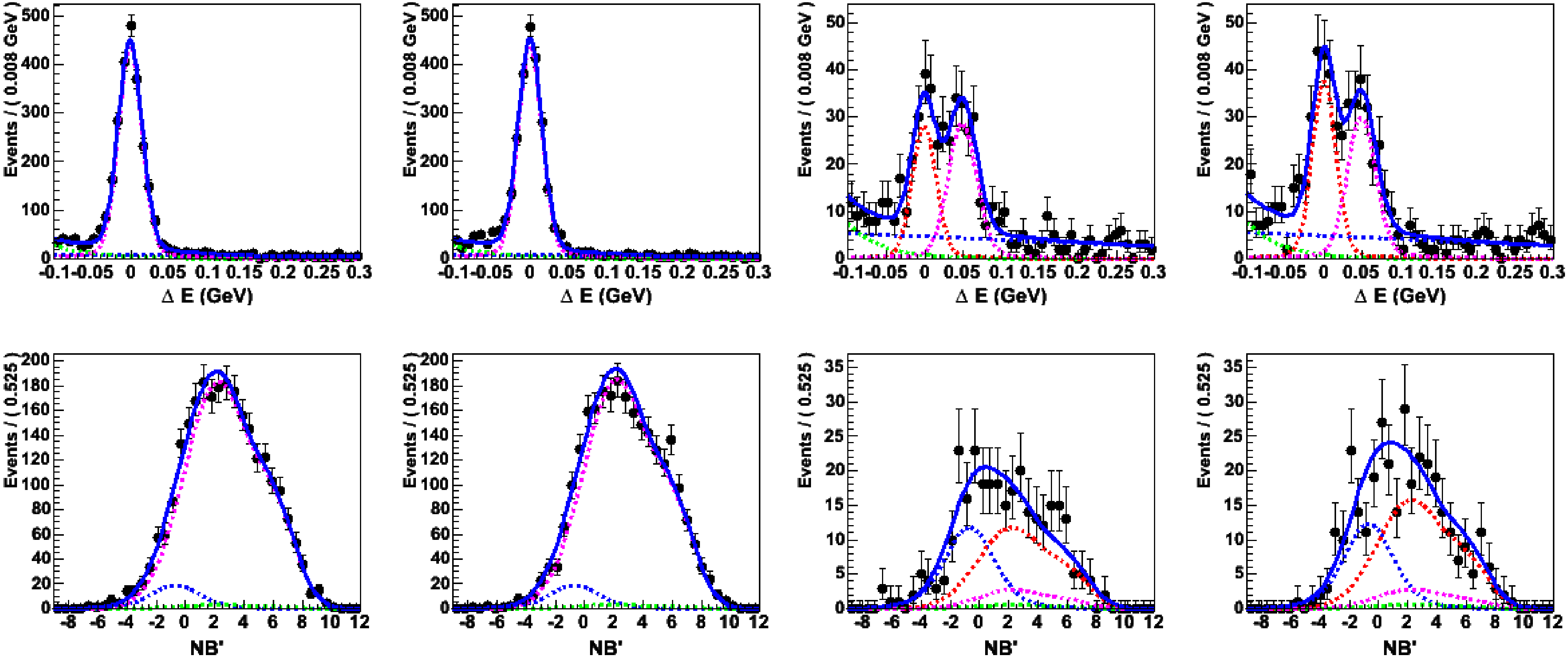
$B \to D\pi$
$B \to DK$
$B\bar{B}$
continuum

$D \to K_S\,\pi^0,\ K_S\,\eta\,(\gamma\gamma)$

Preliminary
LP 2011

h is a pion candidate (KID<0.6) h is a kaon candidate (KID>0.6)

$B^- \to Dh^-$ $B^+ \to Dh^+$ $B^- \to Dh^-$ $B^+ \to Dh^+$



$\Rightarrow\ R_{D_{CP-}} = (8.29 \pm 0.63)\%,\ \ A_{D_{CP-}} = (-12.4 \pm 6.4)\%$

opposite asymmetry !!

GLW Results

Preliminary
LP 2011

Yields	$B \to D\pi$	$B \to DK$
$D \to K\pi$	50432 ± 243	3692 ± 83
$D \to KK, \pi\pi$	7696 ± 106	582 ± 40
$D \to K_S\pi^0, K_S\eta$	5745 ± 91	476 ± 37

$$R_{CP+} = 1.03 \pm 0.07 \pm 0.03$$
$$R_{CP-} = 1.13 \pm 0.09 \pm 0.05$$

$$A_{CP+} = +0.29 \pm 0.06 \pm 0.02$$
$$A_{CP-} = -0.12 \pm 0.06 \pm 0.01$$

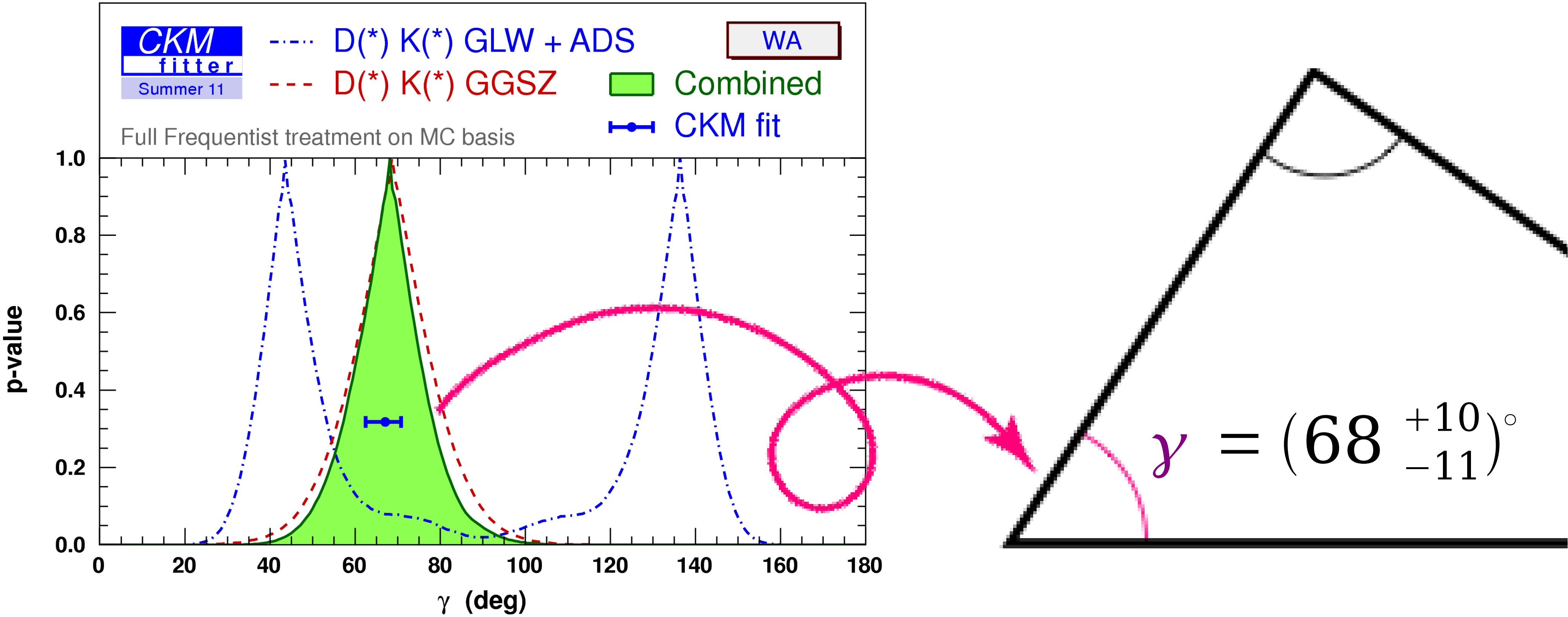
systematics dominated by peaking background,
double ratio approximation

coming improvement: adding $K_S\omega$, $K_S\eta'$ for CP-odd modes

coming update: D^*K modes

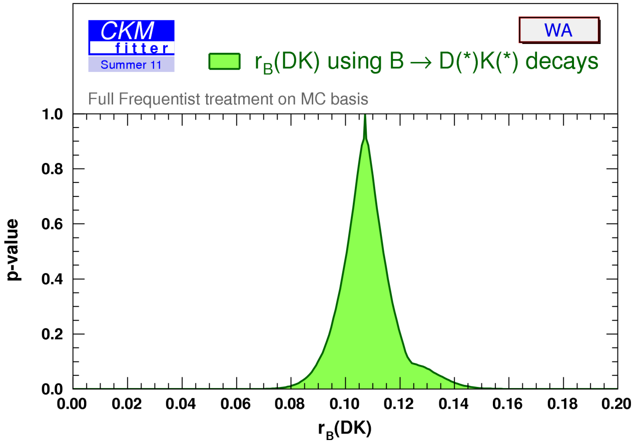
Combined measurements for γ from all methods

http://ckmfitter.in2p3.fr/

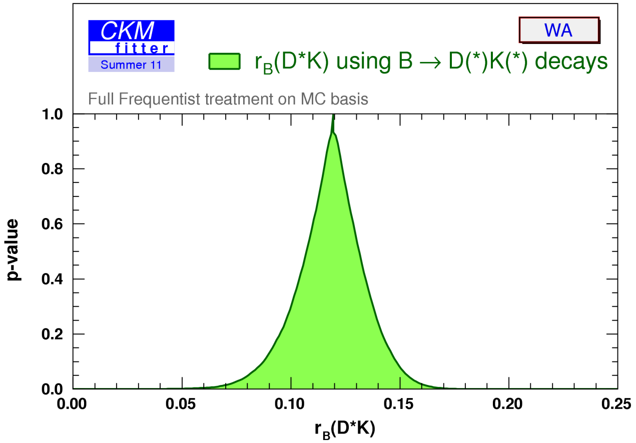


$$\gamma = \left(68\ {}^{+10}_{-11}\right)^{\circ}$$

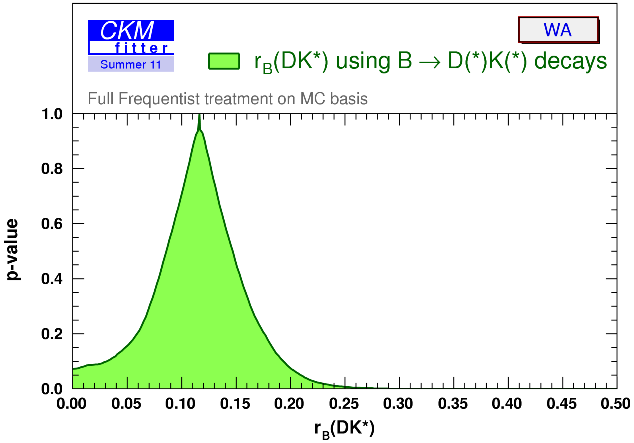
$r_B(DK) = 0.107 \pm 0.010$



$r_B(D^*K) = 0.119\ {}^{+0.018}_{-0.019}$



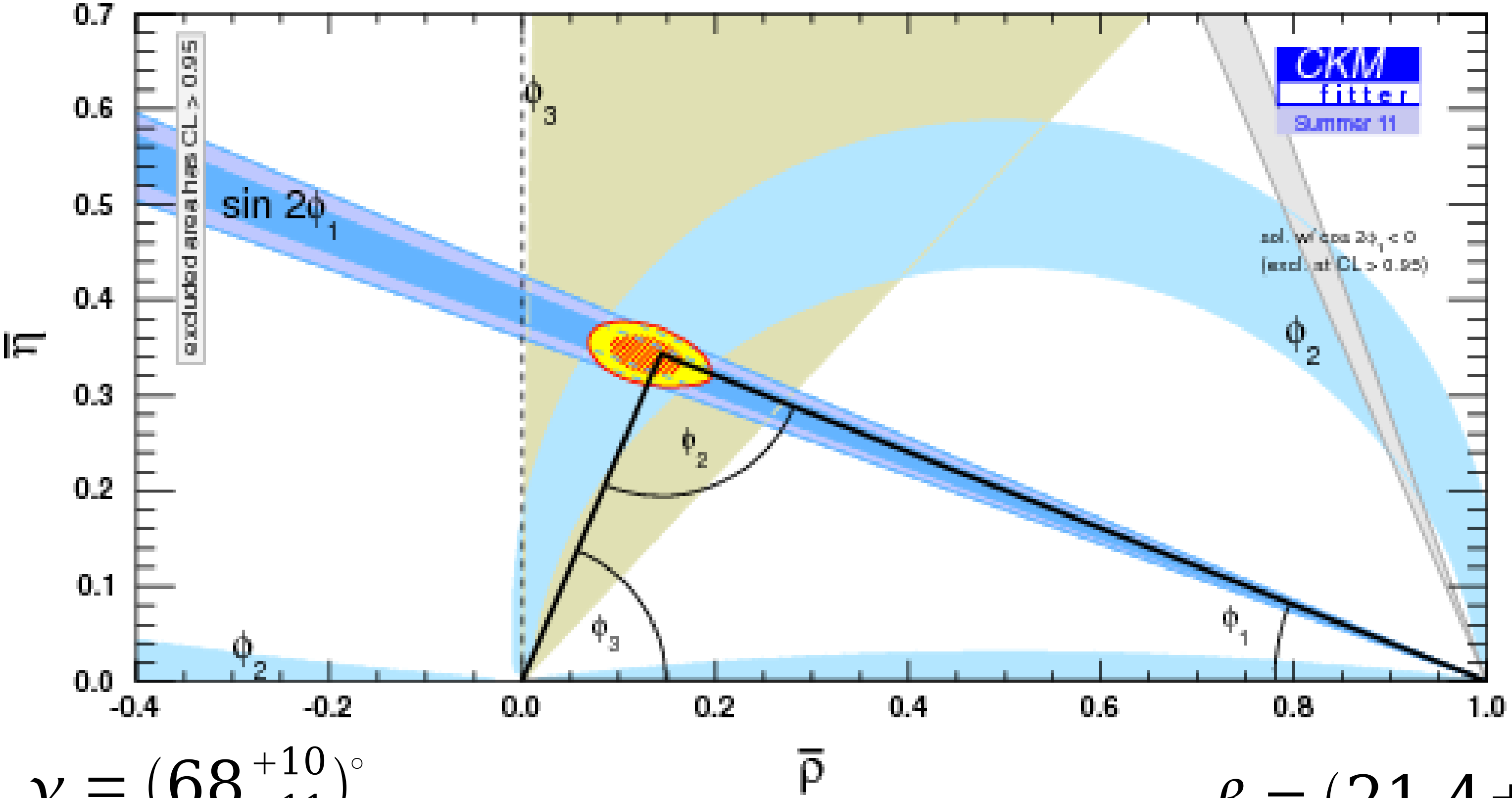
$r_B(D^*K) = 0.116\ {}^{+0.045}_{-0.044}$



Angles only

$$\alpha = (89.0\,^{+4.4}_{-4.2})^{\circ}$$

(WA , CKMfitter , Winter09)

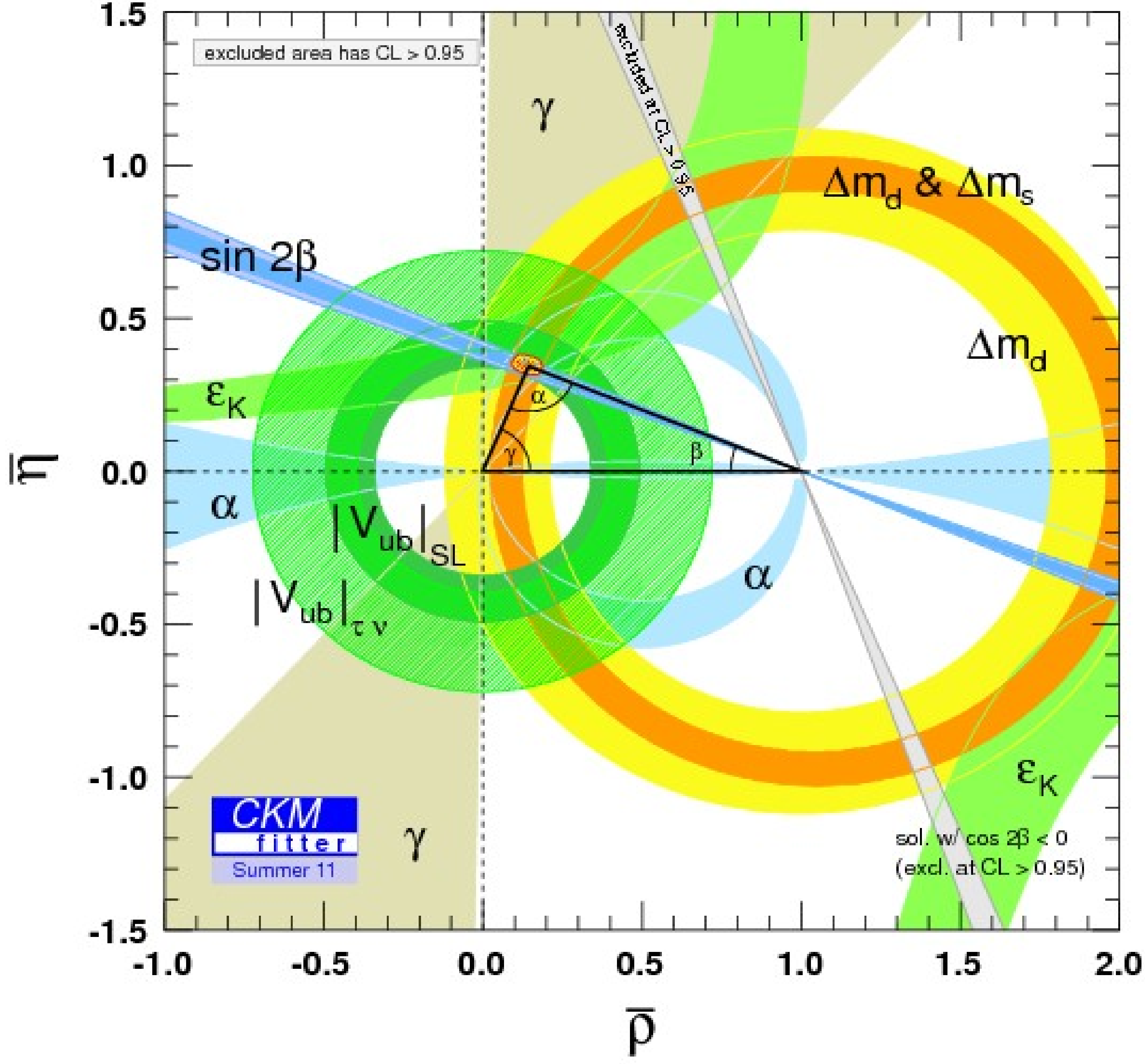


$$\gamma = (68\,^{+10}_{-11})^{\circ}$$

(WA , CKMfitter)

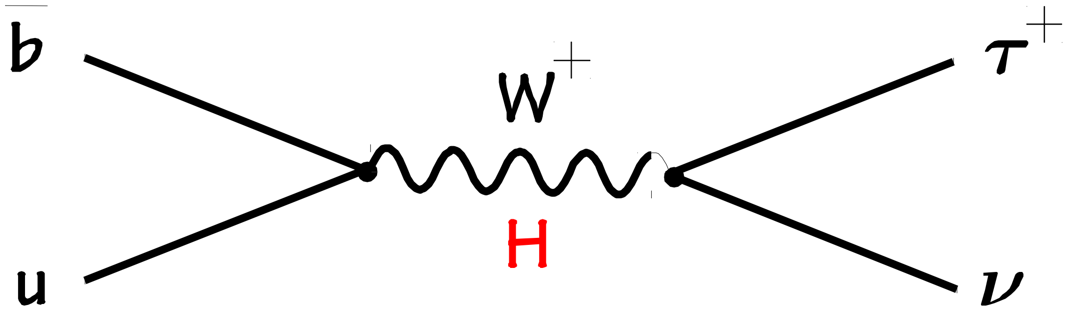
$$\beta = (21.4 \pm 0.8)^{\circ}$$

(WA , HFAG , Winter11)



1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
$\bar{\eta}$
$\bar{\rho}$
excluded area has CL > 0.95
cluded at CL > 0.95
γ
Δm_d & Δm_s
sin 2β
Δm_d
ε_K
α
β
γ
α
$|V_{ub}|_{SL}$
α
$|V_{ub}|_{\tau\nu}$
ε_K
CKM
fitter
Summer 11
γ
sol. w/ cos 2β < 0
(excl. at CL > 0.95)

Tauonic B decays



$$\mathcal{B}_{\mathrm{SM}}(\mathrm{B}^+ \to \tau^+ \nu) = \frac{G_F^2 m_B m_\tau^2}{8\pi}\left(1-\frac{m_\tau^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

$$\text{2HDM (type II)}: \mathcal{B}(\mathrm{B}^+ \to \tau^+ \nu) = \mathcal{B}_{\mathrm{SM}} \times \left(1-\frac{m_B^2}{m_{H^+}^2}\tan^2\beta\right)^2$$

uncertainties from f_B and $|V_{ub}|$ can be reduced to B_B
and other CKM uncertainties by combining with precise Δm_d

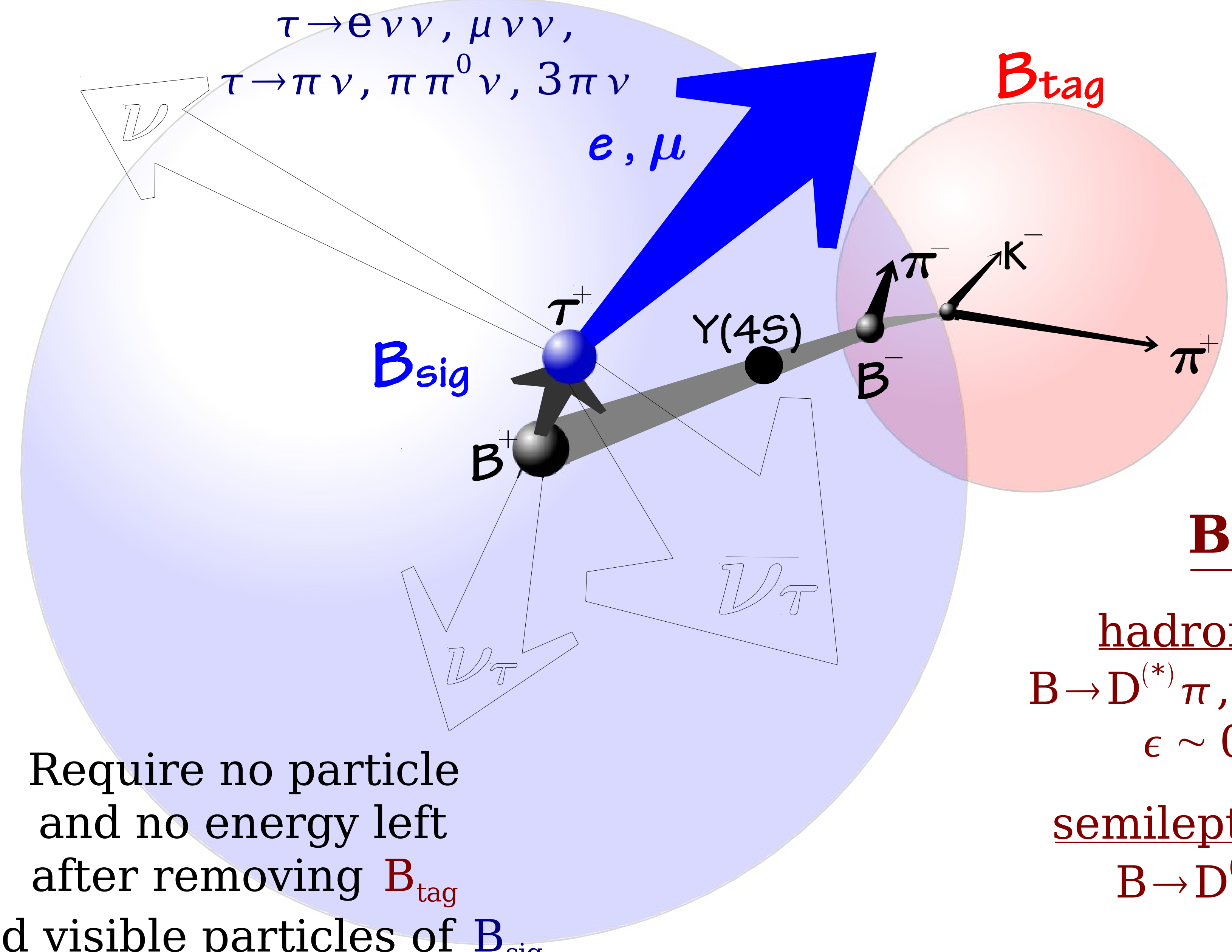
Event reconstruction in $B \to \tau\,\nu$

$B_{sig} \to \tau\,\nu$

(70 % of all τ decays)

$\tau \to e\,\nu\,\nu\,,\ \mu\,\nu\,\nu\,,$

$\tau \to \pi\,\nu\,,\ \pi\,\pi^0\,\nu\,,\ 3\,\pi\,\nu$



Require no particle
and no energy left
after removing B_{tag}
and visible particles of B_{sig}

B_{tag}

hadronic tag

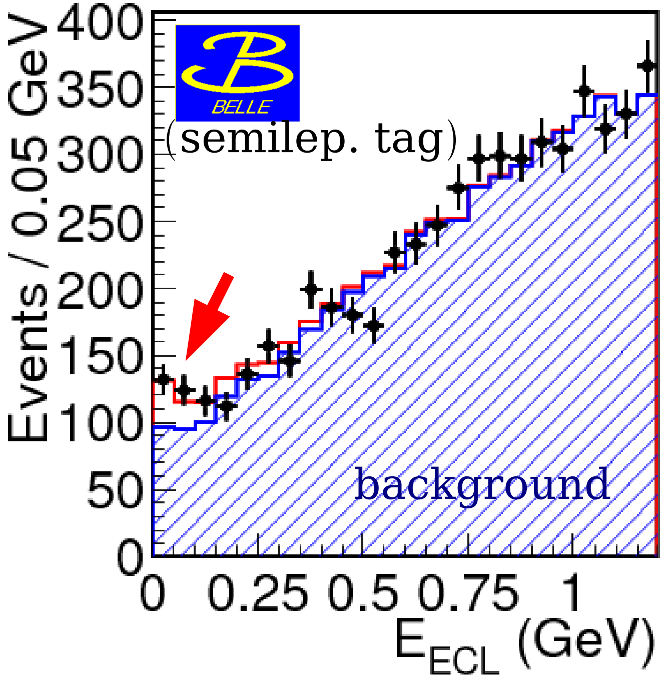
$B \to D^{(*)}\pi\,,\ D^{(*)}$rho....

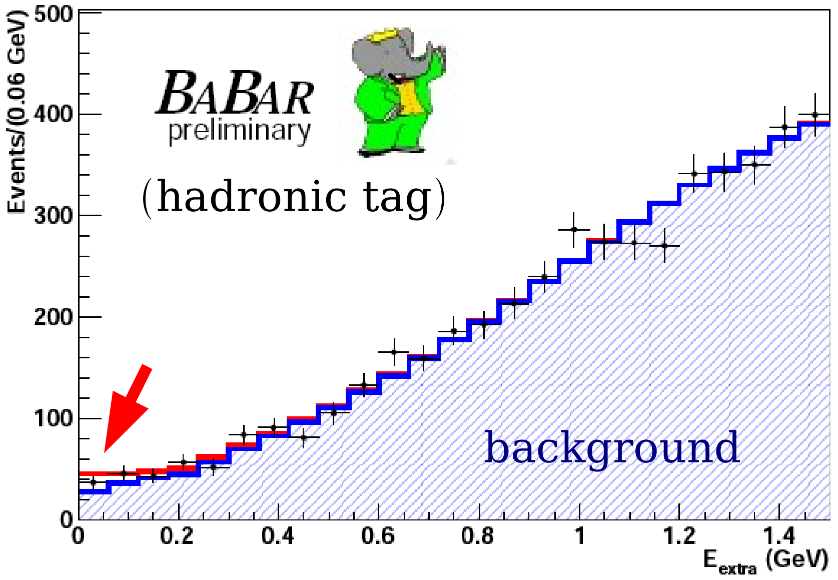
$\epsilon \sim 0.2\,\%$

semileptonic tag

$B \to D^{(*)}\,l\,\nu\ X$

$B^+ \to \tau^+ \nu$ results





Extra calorimeter energy : $E_{ECL/extra}$ (GeV)

	Belle	$N_{B\bar{B}}$	$\boldsymbol{B}$ (10^{-4})	$\Sigma(\sigma)$	
	Hadronic tag	(449 M)	$(1.79^{+0.56}_{-0.49}{}^{+0.46}_{-0.51})$	3.5	PRL97 , 251802 (2006)
⇒	Semilep. tag	(657 M)	$(1.54^{+0.38}_{-0.37}{}^{+0.29}_{-0.31})$	3.6	PRD 82, 071101 (2010)
	BaBar				
⇒	Hadronic tag	(468 M)	$(1.80^{+0.57}_{-0.54} \pm 0.26)$	3.6	preliminary
	Semilep. tag	(459 M)	$(1.7 \pm 0.8 \pm 0.2)$	2.3	PRD81 , 051101 (2010)

$B^+ \to \tau^+ \nu$ results

World average: $\mathcal{B}(B^+ \to \tau^+ \nu) = (1.68 \pm 0.31) \times 10^{-4}$

$$\mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (1.20 \pm 0.25) \times 10^{-4}$$

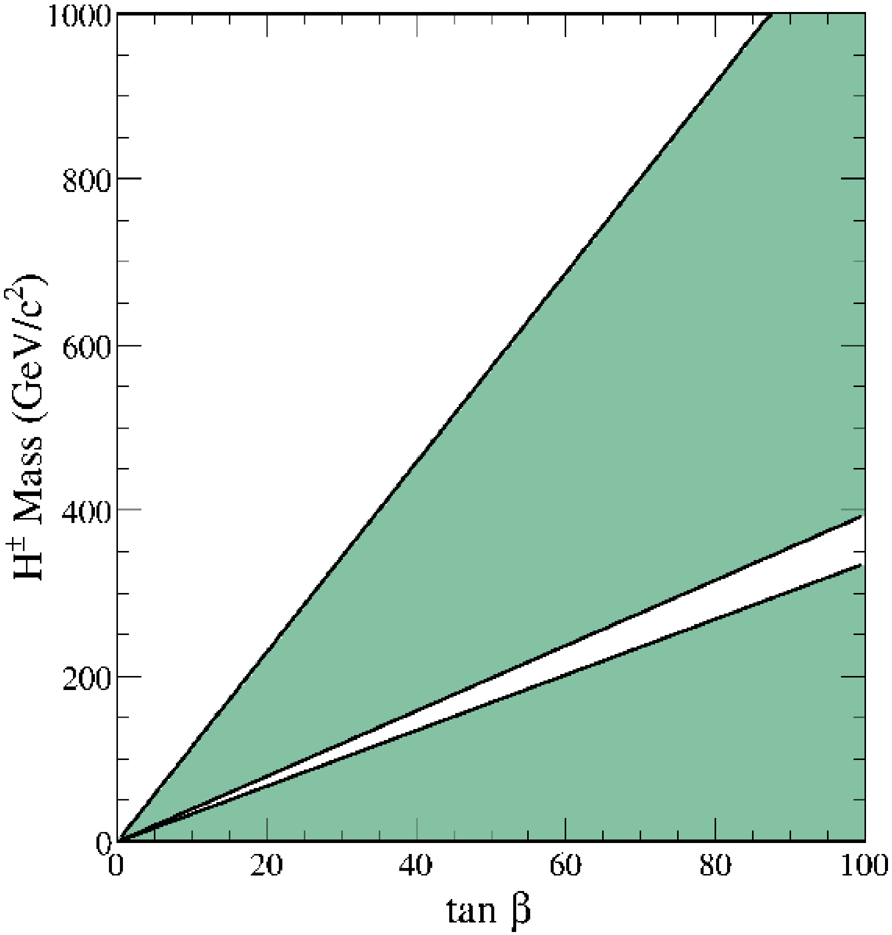
using f_B (HPQCD), $|V_{ub}|$ (HFAG)

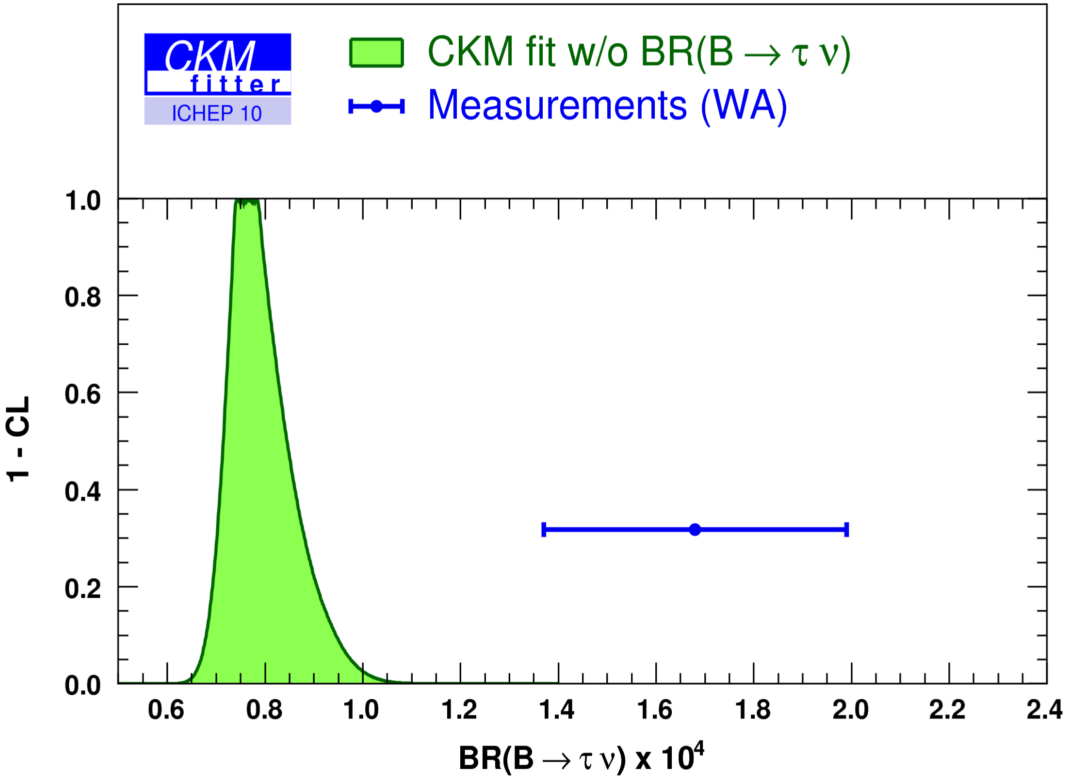
$$\text{CKMfitter}: \mathcal{B}_{SM}(B^+ \to \tau^+ \nu) = (0.76^{+0.11}_{-0.06}) \times 10^{-4}$$

2.8σ difference

2HDM (type II):

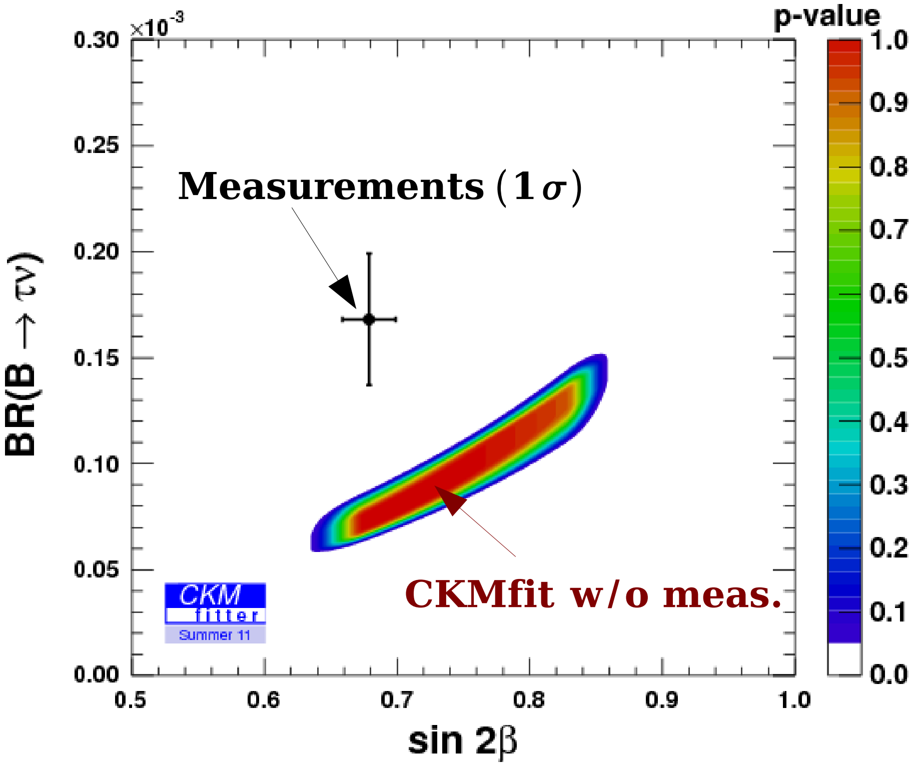
$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2 \beta\right)^2$$





$B^+ \to \tau^+ \nu$ versus…

… $\sin 2\beta_{cc}$



⇒ within the SM, either the observed $\mathrm{BR}[B \to \tau \nu]$ is too high, either $\sin 2\beta_{cc}$ is too low

… $|V_{ub}|$ [A.Khodjamirian et al, arXiv:1103.2655]

$$R_{s/l}(q_1^2, q_2^2) \equiv \frac{\Delta B_{B\to\pi l\nu}(q_1^2, q_2^2)}{B(B\to\tau\nu_\tau)} \left(\frac{\tau_{B^-}}{\tau_{B^0}}\right)$$

high q^2: comparison with lattice QCD results:

$$R_{s/l} = 0.20^{+0.08}_{-0.05}\ (\mathrm{BaBar}),\ 0.28^{+0.13}_{-0.07}\ (\mathrm{Belle})$$

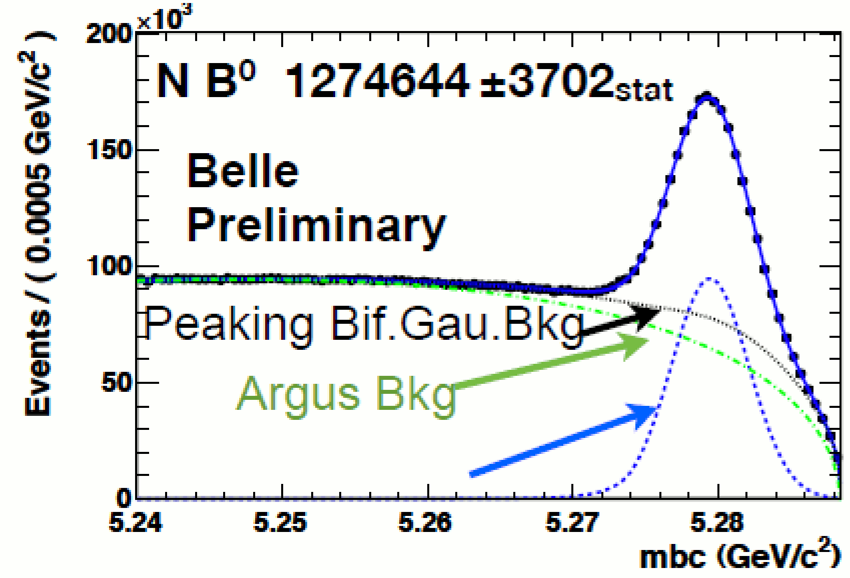
$$= 0.52 \pm 0.16\ (\mathrm{HPQCD}),\ 0.46 \pm 0.10\ (\mathrm{FNAL/MILC})$$

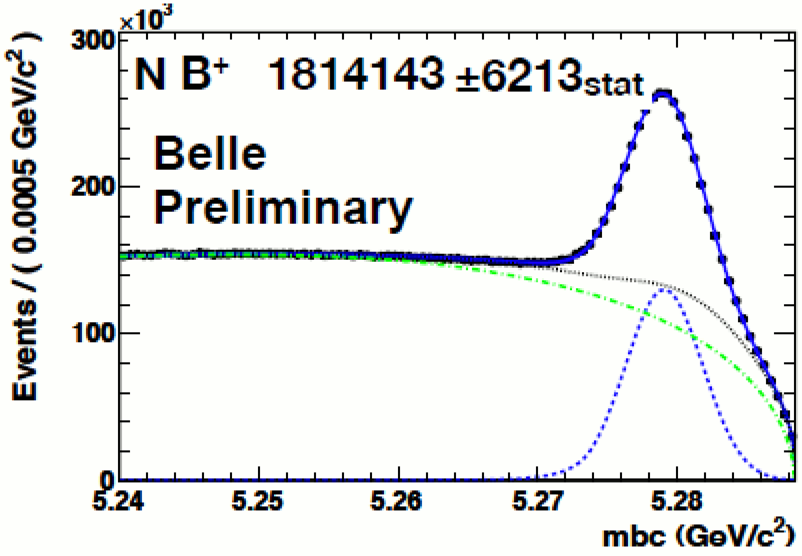
low q^2: similar discrepancy btw data QCD sum rule

⇒ important to update $B(B \to \tau \nu)$

New full reconstruction

- reprocessed data sample with improved tracking efficiency
- none of the results shown for rare B decays use full data sample yet
- **had tag efficiency improved: effective luminosity increased by factor > ×2**

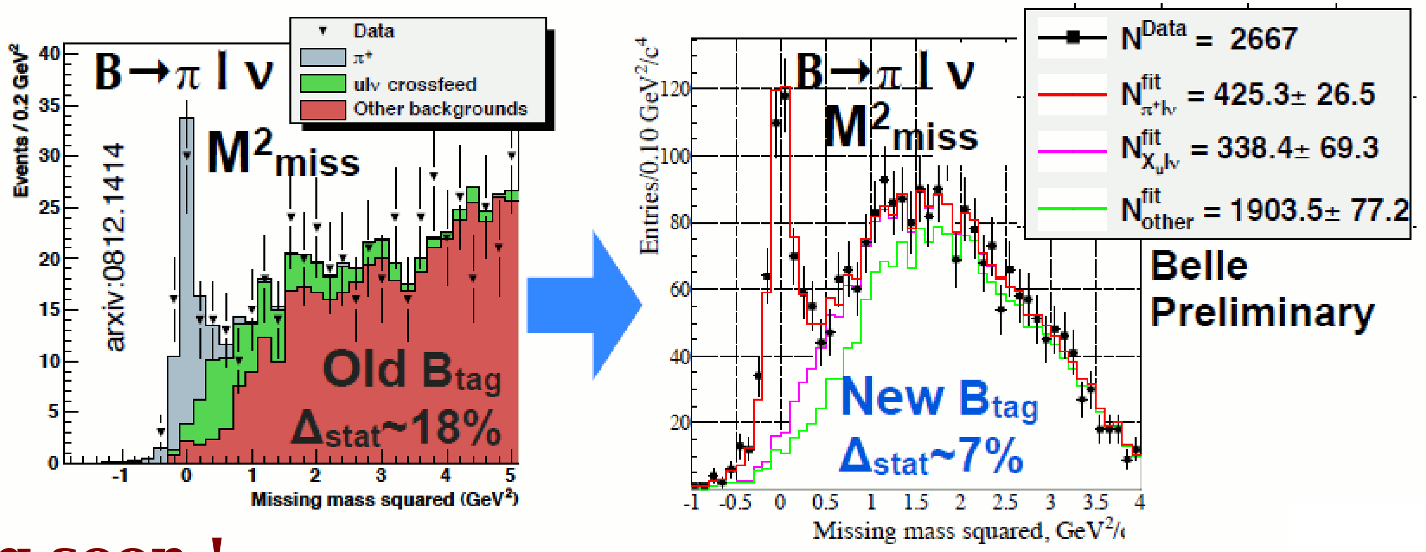




All hadron tag B analyses (leptonic and semileptonic decays) **are being reviewed**

e.g. $B \to \pi l \nu$

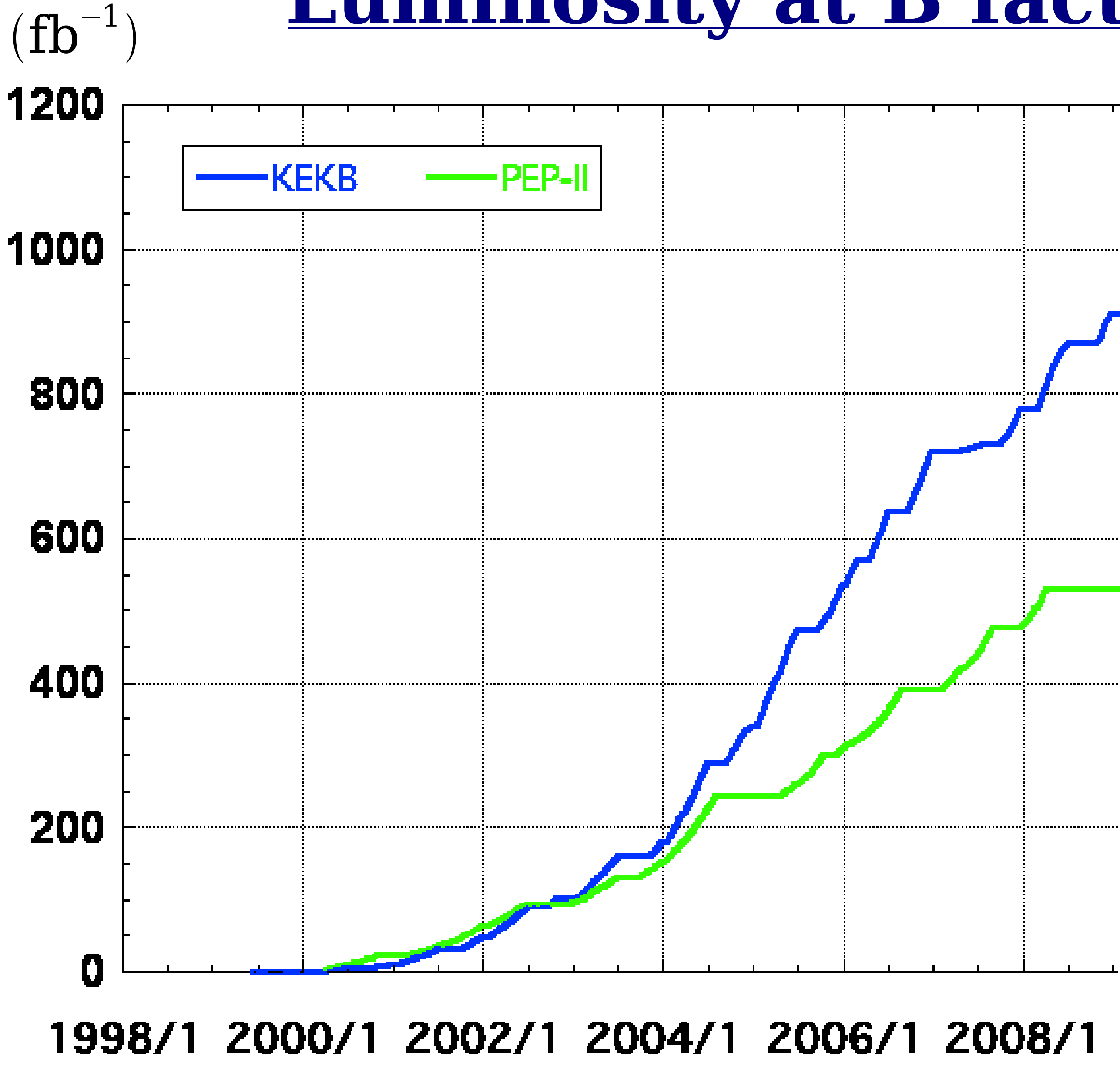
(teaser !)



⇒ new results coming soon !

$B \to \tau \nu$, $\mu \nu$, $K^{(*)} \nu \bar{\nu}$, exclusive $b \to u l \nu$, $D^{(*)} \tau$ nu...

Luminosity at B factories



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

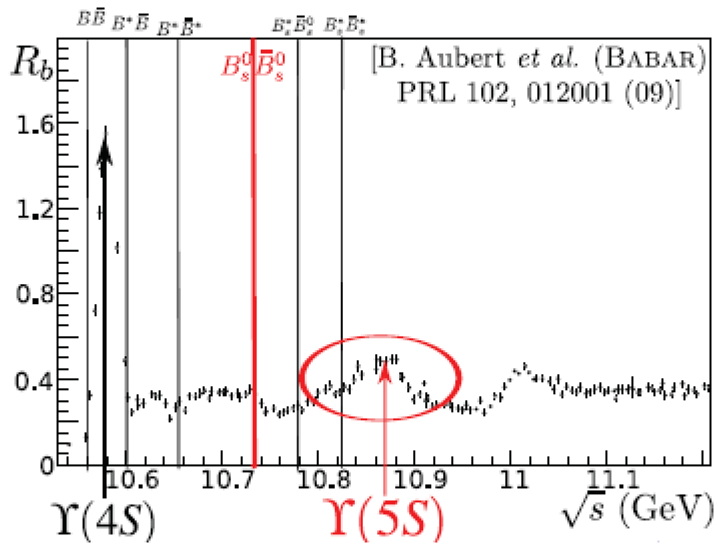
Υ(3S): 3 fb^{-1}

Υ(2S): 24 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan:

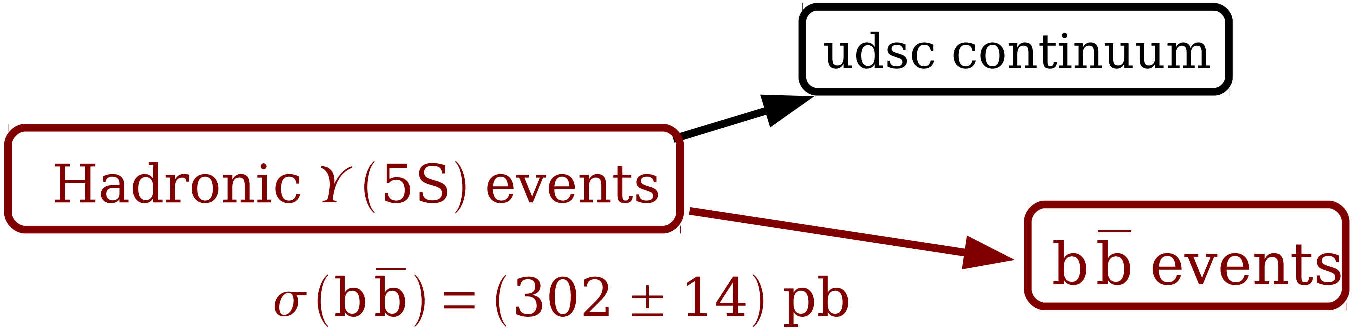
~ 100 fb^{-1}



[B. Aubert *et al.* (BABAR) PRL 102, 012001 (09)]

Data taken at Υ(5S) ($\sqrt{s}$ = 10867 ± 1 MeV)

B_s production at $\Upsilon(5S)$



udsc continuum

Hadronic $\Upsilon(5S)$ events

$b\bar{b}$ events

$\sigma(b\bar{b}) = (302 \pm 14)$ pb

Cleo (PRD 75, 012002)
Belle (PRL 98, 052001)

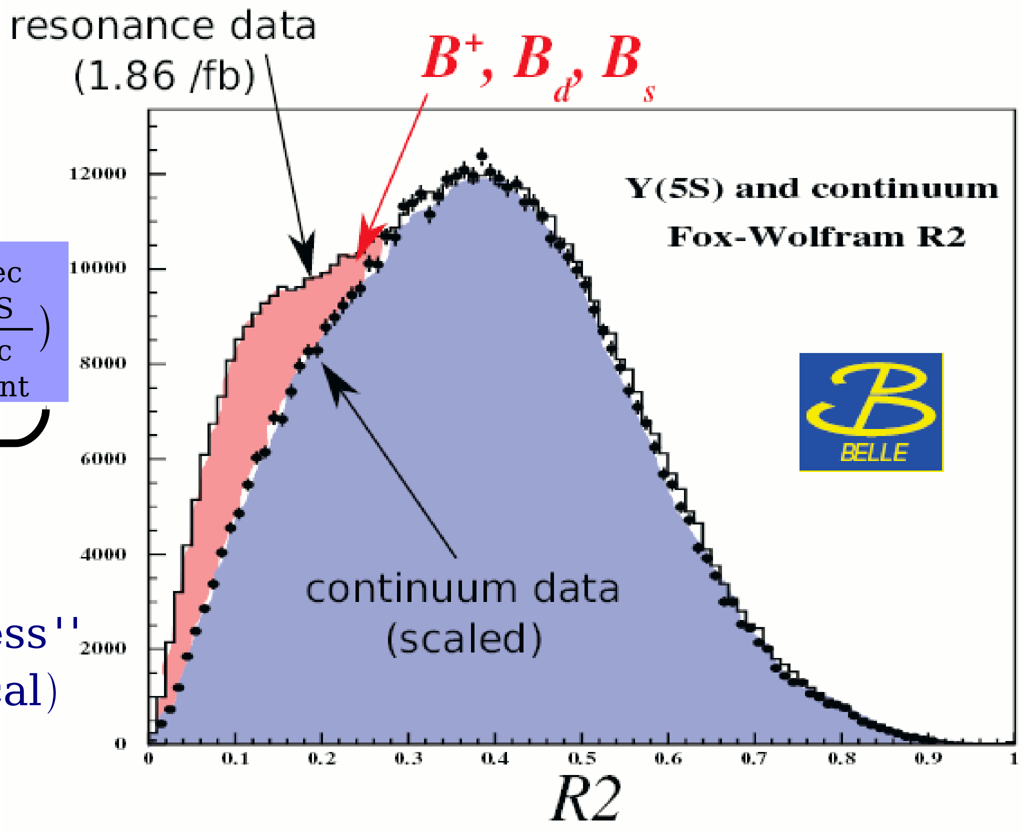
$b\bar{b}$ cross section : subtraction of taken below open-beauty threshold

$$\sigma(b\bar{b}) = \frac{N^{b\bar{b}}_{5S}}{L_{5S}}$$

$$= \frac{1}{L_{5S}} \frac{1}{\epsilon^{b\bar{b}}_{5S}} \left(N^{had}_{5S} - \underbrace{N^{had}_{cont} \frac{L_{5S}}{L_{cont}} \frac{E^2_{cont}}{E^2_{5S}} \frac{\epsilon^{rec}_{5S}}{\epsilon^{rec}_{cont}}}_{\text{scaling factor}}\right)$$

Continuum data below open-beauty threshold

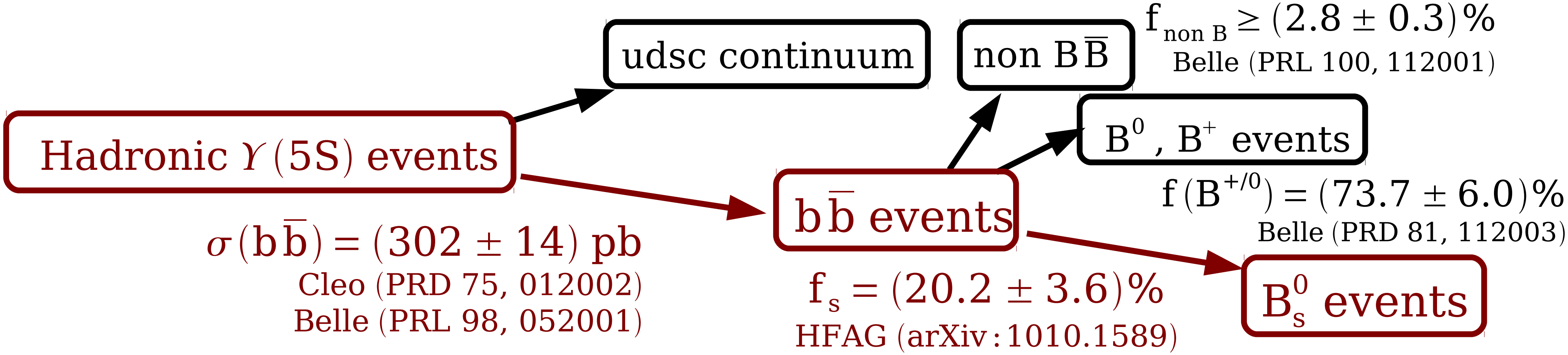
On resonance data



R_2: 2nd Fox-Wolfram moment ~ event ''jettiness''
→ smaller values for $B\bar{B}$ events (more spherical)

(measurement done with 1.86 fb^{-1})

B_s production at $\Upsilon(5S)$



udsc continuum

non $B\bar{B}$

$f_{\text{non }B} \geq (2.8 \pm 0.3)\%$
Belle (PRL 100, 112001)

B^0, B^+ events

Hadronic $\Upsilon(5S)$ events

$b\bar{b}$ events

$f(B^{+/0}) = (73.7 \pm 6.0)\%$
Belle (PRD 81, 112003)

$\sigma(b\bar{b}) = (302 \pm 14)$ pb
Cleo (PRD 75, 012002)
Belle (PRL 98, 052001)

$f_s = (20.2 \pm 3.6)\%$
HFAG (arXiv:1010.1589)

B_s^0 events

f_s = fraction of B_s. Inclusive measurements:

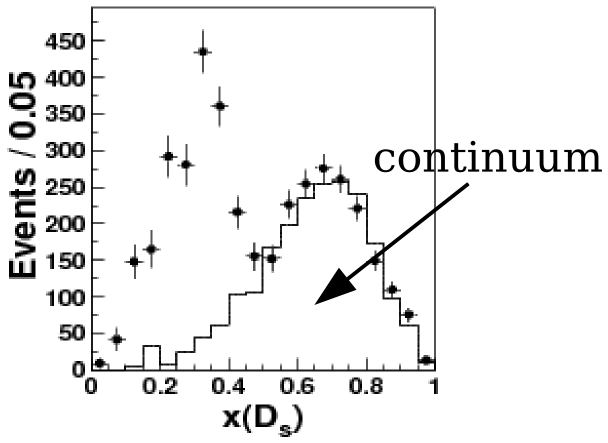
$$\underbrace{\frac{1}{2}\mathcal{B}(\Upsilon(5S)\to D_s X)}_{\Upsilon(5S)\text{ data}} = f_s \times \underbrace{\mathcal{B}(B_s \to D_s X)}_{\text{model-dependent estimate}} + (1-f_s)\times \underbrace{\mathcal{B}(B \to D_s X)}_{\Upsilon(4S)\text{ data}}$$

15% uncertainty, mainly due to model-dependent estimate

⇒ dominant systematics for our branching fractions

In 121 fb^{-1}:
$N_{B_s^0} = 2\, L_{int} \,.\, \sigma(b\bar{b}) \,.\, f_s \approx 14 \times 10^6$

measurement with 1.86 fb^{-1}



B_s production at $\Upsilon(5S)$

3 productions modes:

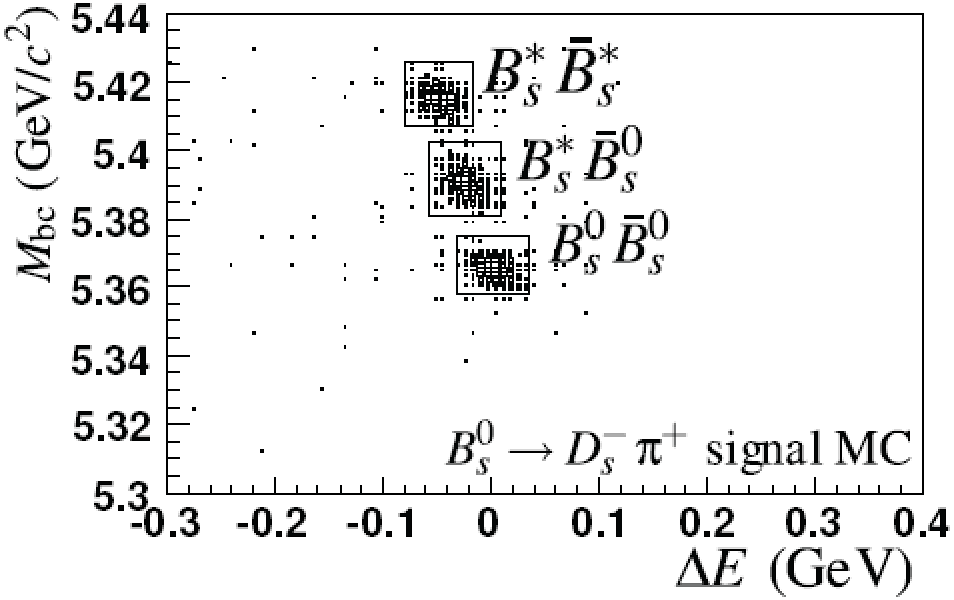
$$\Upsilon(5S) \rightarrow B_s^* \overline{B}_s^*, \ \Upsilon(5S) \rightarrow B_s^* \overline{B}_s^0, \ \Upsilon(5S) \rightarrow B_s^0 \overline{B}_s^0$$

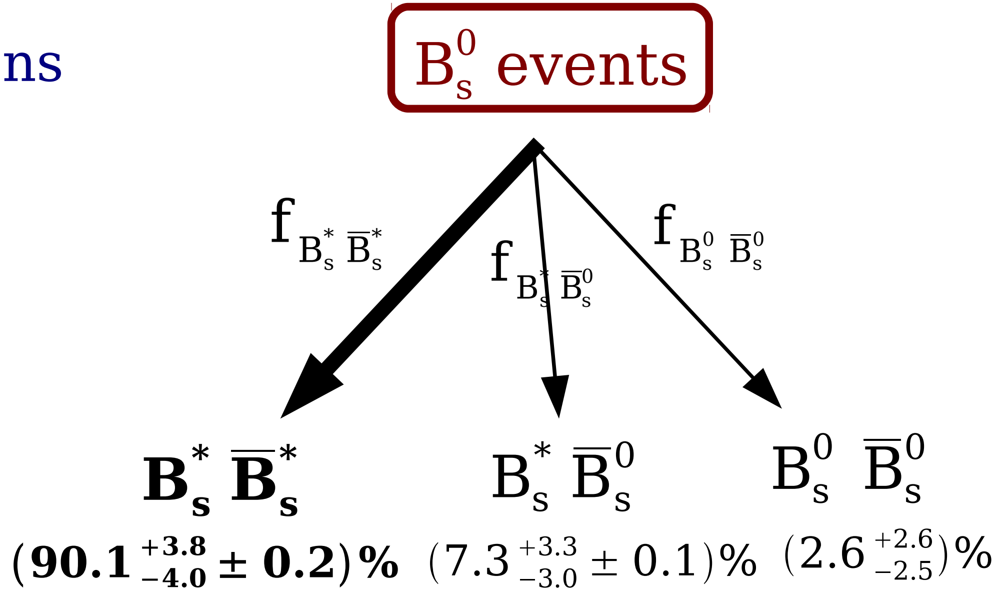
$B_s^* \rightarrow B_s^0 \gamma$ is not reconstructed (γ too soft)

Full reconstruction of the B_s^0 with observables: $(E_b^* = \sqrt{s}/2)$

- **Beam-constrained mass: $M_{bc} = \sqrt{E_b^{*2} - p_{B_s^0}^{*\ 2}}$**
- **Energy difference: $\Delta E = E_{B_s^0}^* - E_b$**

$\Rightarrow$ B_s^0 candidates are in 3 signal regions





B_s^0 events

$f_{B_s^* \overline{B}_s^*}$

$f_{B_s^* \overline{B}_s^0}$

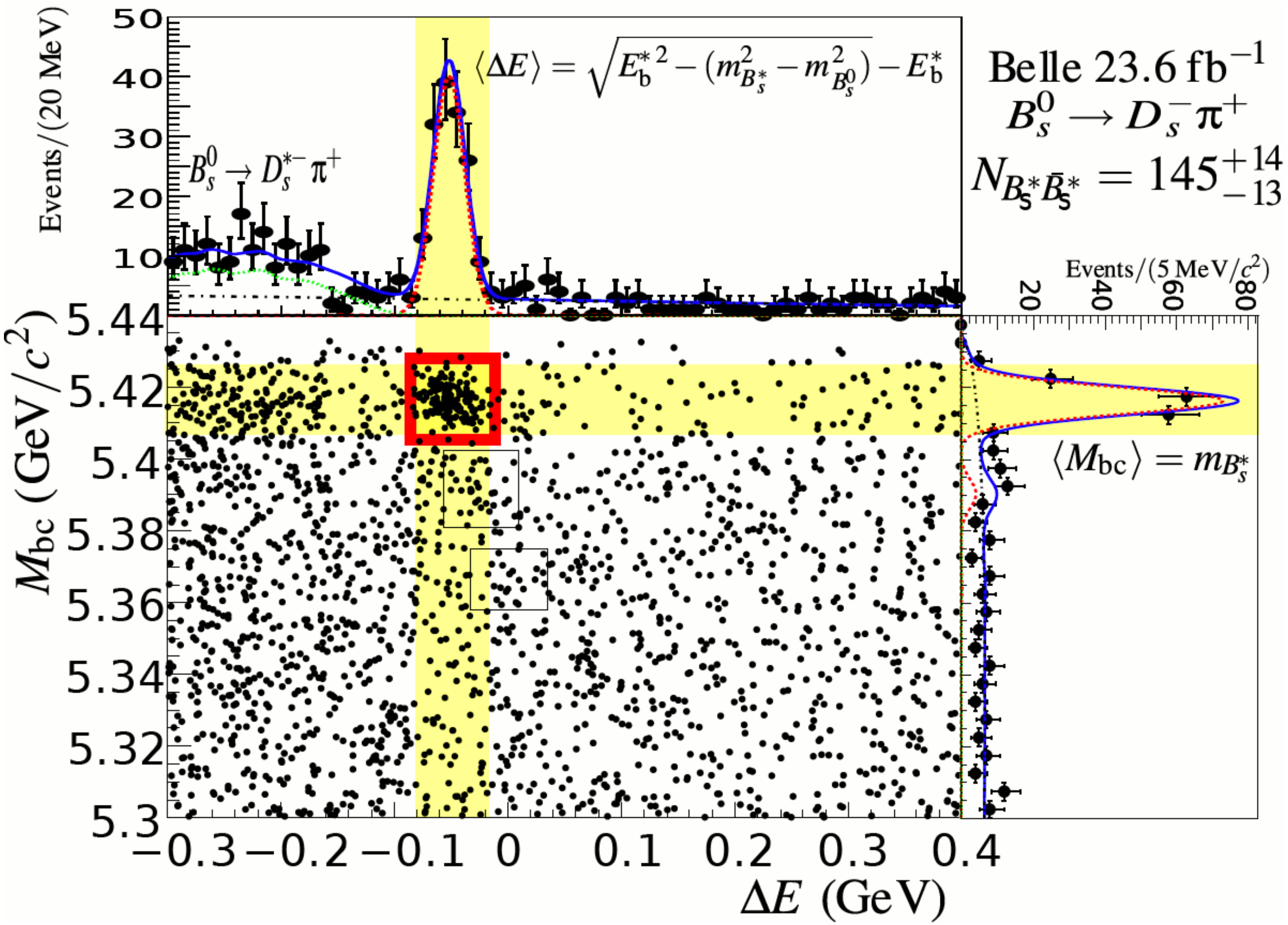
$f_{B_s^0 \overline{B}_s^0}$

$B_s^* \overline{B}_s^*$	$B_s^* \overline{B}_s^0$	$B_s^0 \ \overline{B}_s^0$
$(90.1^{+3.8}_{-4.0} \pm 0.2)\%$	$(7.3^{+3.3}_{-3.0} \pm 0.1)\%$	$(2.6^{+2.6}_{-2.5})\%$

Belle (PRL 102, 021801)

Study of $B_s^0 \rightarrow D_s^- \pi^+$

Phys. Rev. Lett. **102,** 021801 (2009)



$$f_{B_s^*\bar{B}_s^*} = (90.1^{+3.8}_{-4.0} \pm 0.2)\%$$

$$m_{B_s^*} = (5416.4 \pm 0.4 \pm 0.5)\ \mathrm{MeV}/c^2$$

$$m_{B_s^0} = (5364.4 \pm 1.3 \pm 0.7)\ \mathrm{MeV}/c^2$$

$$\boxed{\mathcal{B}\,(B_s^0 \rightarrow D_s^- \pi^+) = (3.67\ {}^{+0.35}_{-0.33}\ {}^{+0.43}_{-0.42} \pm 0.49\ (f_s)) \times 10^{-3}}$$

- 20% uncertainties, f_s is a crucial source of systematics
- large $f_{B_s^*B_s^*}$ confirmed (1st Belle value: $(93^{+7}_{-9} \pm 1)\%$ [PRD 76, 012002 (07)])
- $m_{B_s^*}$ is 2.6σ larger than CLEO [PRL 96, 152001 (06)]
- $m_{B_s^*}$ (m_{B_s}) is the 1st (2nd) most precise measurement so far

$B_s \to$ CP eigenstates decays and more…

- CP eigenstates:
  - $B_s \to KK$
  - $B_s \to J/\psi\,\phi$ (especially BR)
  - $B_s \to J/\psi\,f_0(980)$ (silver mode at LHCb to measure β_s)
  - $B_s \to J/\psi\,\eta,\ J/\psi\,\eta',\ J/\psi\,K^0_S$ …

⇒ **the first step is to establish these modes !**

⇒ **decays with π^0 and/or γ are difficult for hadron-collider experiments**

- $B^0_s \to D_s^{(*)+} D_s^{(*)-}$ dominates $\Delta\Gamma_s$

$$\Delta\Gamma^{CP} = \Gamma(\text{CP-even}) - \Gamma(\text{CP-odd}) \approx \Gamma(B^0_s \to D_s^{(*)+} D_s^{(*)-})$$

- CKM-favored and CP-even eigenstate (in heavy-quark limit)
- Dominates $\Delta\Gamma$ (this relation has few % theoretical uncertainty)

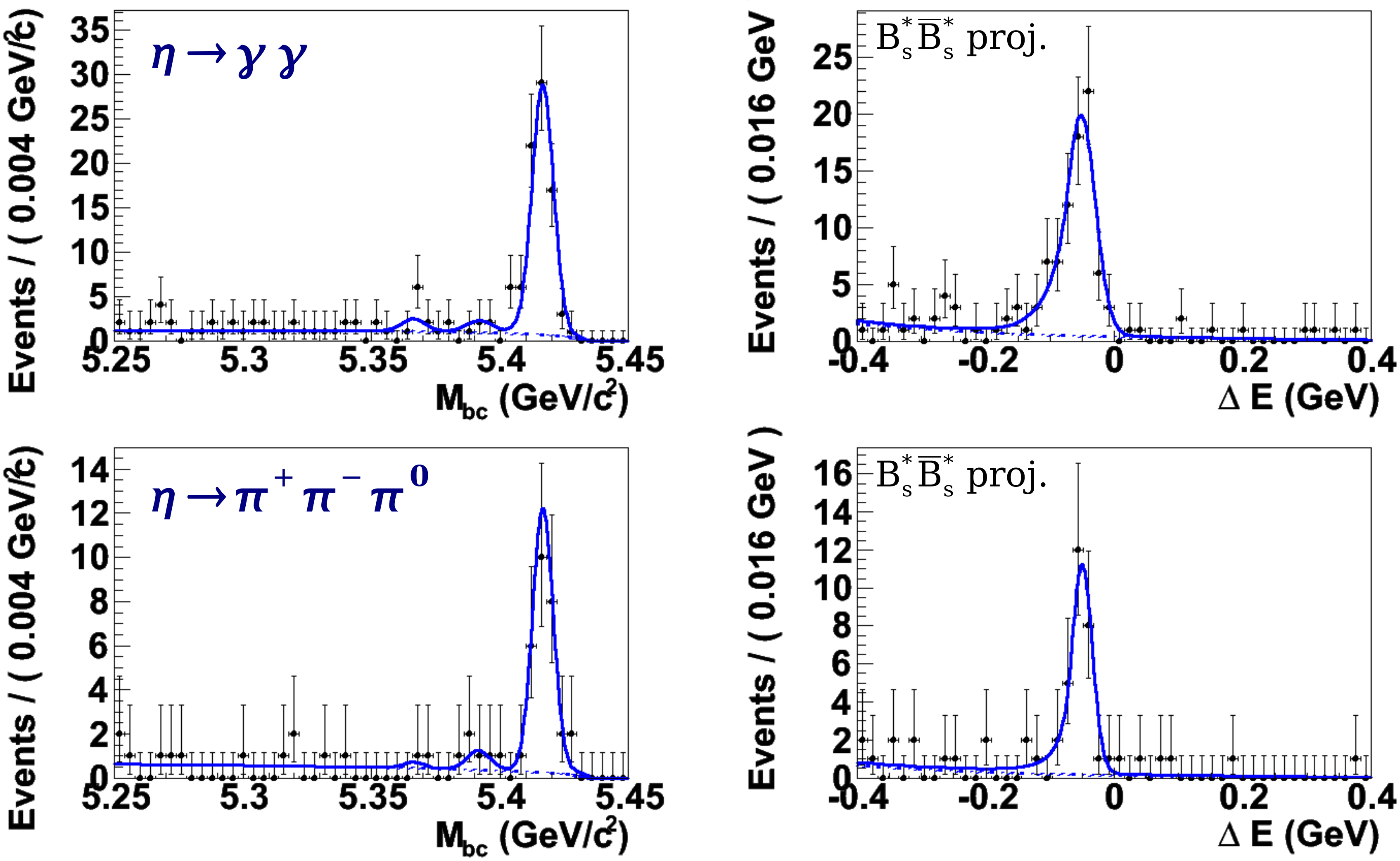
$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \approx \frac{2 \times \mathcal{B}(B^0_S \to D_s^{(*)+} D_s^{(*)-})}{1 - \mathcal{B}(B^0_S \to D_s^{(*)+} D_s^{(*)-})}$$

R.Aleksan et al., Phys. Lett. B 316, 567 (1993)

$B_s^0 \to$ CP-eigenstate Decay Modes

- Large data sample recorded at $\Upsilon(5S)$ $(121\ \mathrm{fb}^{-1})$
- Precise measurements of exclusive modes, including CP modes
  for example, ''Observation of $B_S^0 \to J/\psi f_0(980)$...'', PRL 106, 121802 (2011)
- **$B_s \to J/\psi\,\eta$ in $\eta \to \gamma\gamma$, $\eta \to \pi^+\pi^-\pi^0$ channels**

new Belle results with 121 fb^{-1}



$$\boxed{\mathbf{Br(B_s \to J/\psi\,\eta) = (5.11 \pm 0.50\,(stat) \pm 0.35\,(syst) \pm 0.68\,(f_s)) \times 10^{-4}}}$$

$B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$ Analysis

Preliminary, summer 2011

- CP-even final states
  - $D_s^+ D_s^-$ pure CP-even
  - $D_s^* D_s^{(*)}$ predominantly CP-even

- In the heavy-quark limit, while $(m_b - 2m_c) \rightarrow 0$ and $N_c \rightarrow \infty$
  - $b \rightarrow c\bar{c}s$ processes contribute constructively to $\Delta\Gamma_s$
  - $\Gamma[B_s^0(CP+) \rightarrow D_s D_s]$ saturates $\Delta\Gamma_s^{CP}$
  - assuming negligible CP violation, we can estimate $\Delta\Gamma_s/\Gamma_s$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \frac{2 \times \mathcal{B}(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})}{1 - \mathcal{B}(B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-})}$$

R.Aleksan et al., Phys. Lett. B 316, 567 (1993)

- Full reconstruction of $B_s^0 \rightarrow D_s^{(*)+} D_s^{(*)-}$: large B.R. $(\sim 10^{-2})$ but low efficiency $(\sim 10^{-4})$

- D_s^+ reconstructed in 6 final states: $\phi\pi^+$, $K_S^0 K^+$, $\overline{K}^{*0} K^+$, $\phi\rho^+$, $K_S^0 K^{*+}$ and $\overline{K}^{*0} K^{*+}$

- $D_s^{*+} \rightarrow D_s^+ \gamma$: photon energy is low $(E_\gamma < 150$ MeV$)$!

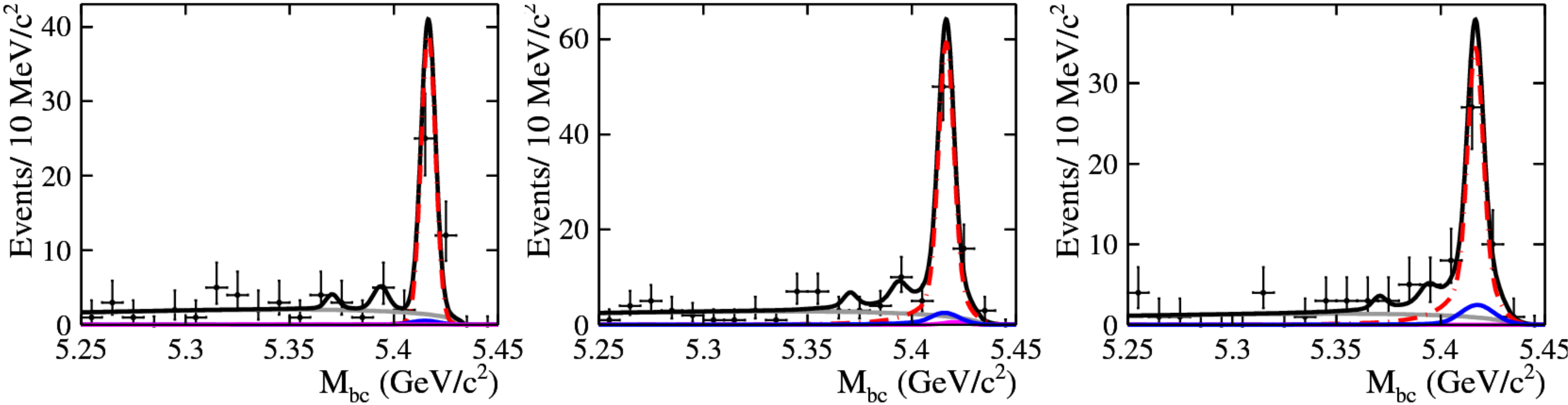
- Contamination between the 3 modes (cross feed) when a photon is missing or added by error

Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$

Preliminary
summer 2011

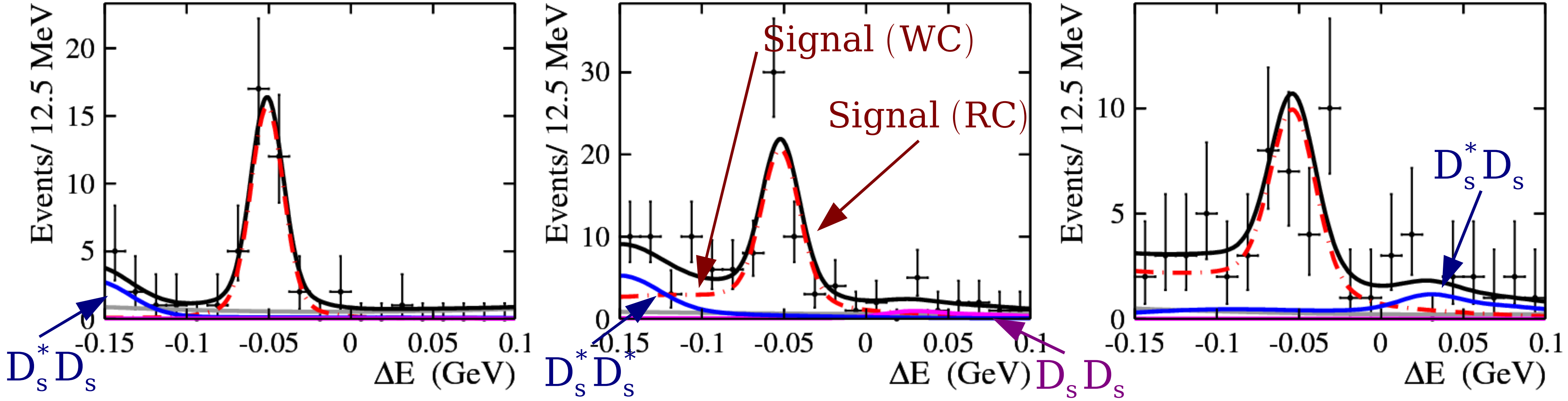
- Simultaneous fit of the 3 modes. For each mode, cross feed from the 2 others is included
- Signal has 2 components: right and wrong combinations

select events in $\Delta E \in [-0.1, 0.0]$



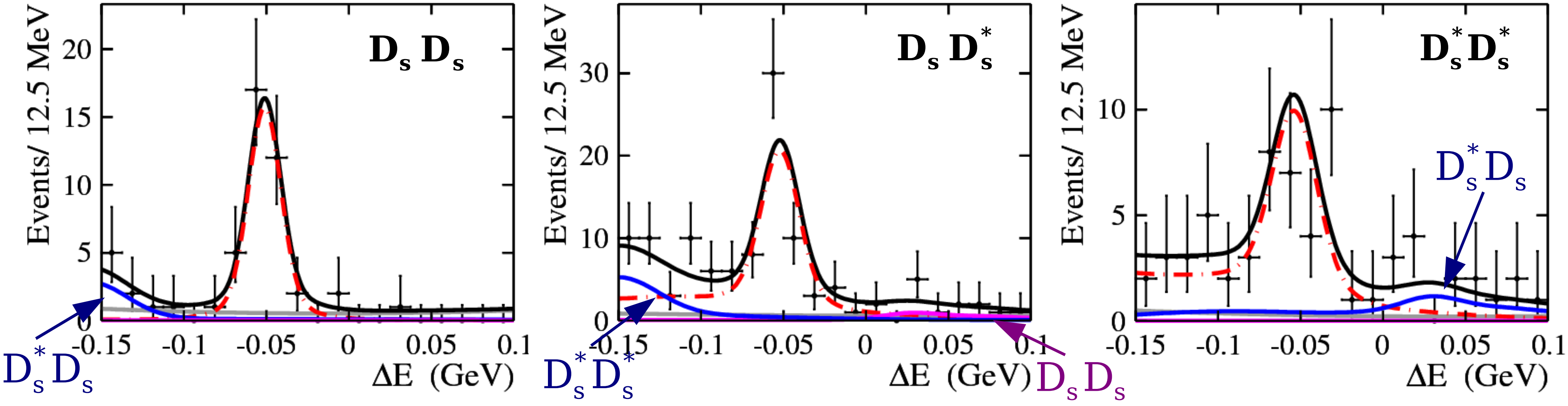
$N_S(D_s^{\pm} D_s^{\mp}) = 33.1^{+6.0}_{-5.4}$ (11.6σ) $N_S(D_s^{*\pm} D_s^{\mp}) = 44.5^{+5.8}_{-5.5}$ (13.3σ) $N_S(D_s^{*\pm} D_s^{*\mp}) = 24.4^{+4.1}_{-3.6}$ (8.6σ)

select events in $M_{bc} \in [5.4, 5.43]$



Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$

Preliminary, summer 2011



⇒ 3 modes are seen separately (102 signal events)

$B\,(B_s^0 \to D_s^+ D_s^-) = (0.58^{+0.11}_{-0.09} \pm 0.13)\%$

consistent with CDF [PRL 100, 021803]

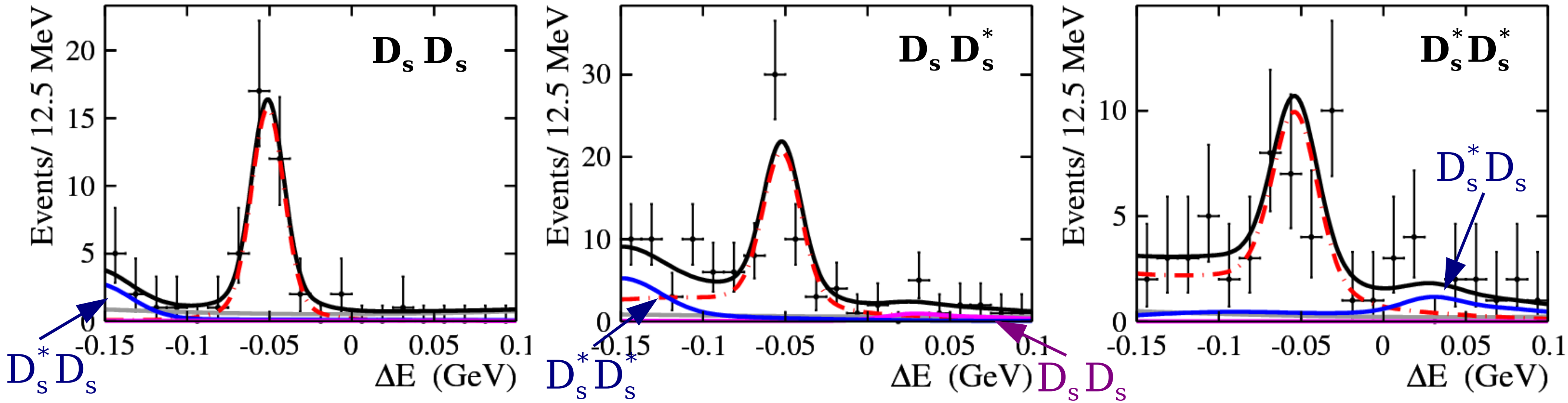
$B\,(B_s^0 \to D_s^{*\pm} D_s^{\mp}) = (1.8 \pm 0.2 \pm 0.4)\%$ ⇒ $\boldsymbol{B\,(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%}$

$B\,(B_s^0 \to D_s^{*+} D_s^{*-}) = (2.0 \pm 0.3 \pm 0.5)\%$

first observation

Observation of $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$

Preliminary, summer 2011

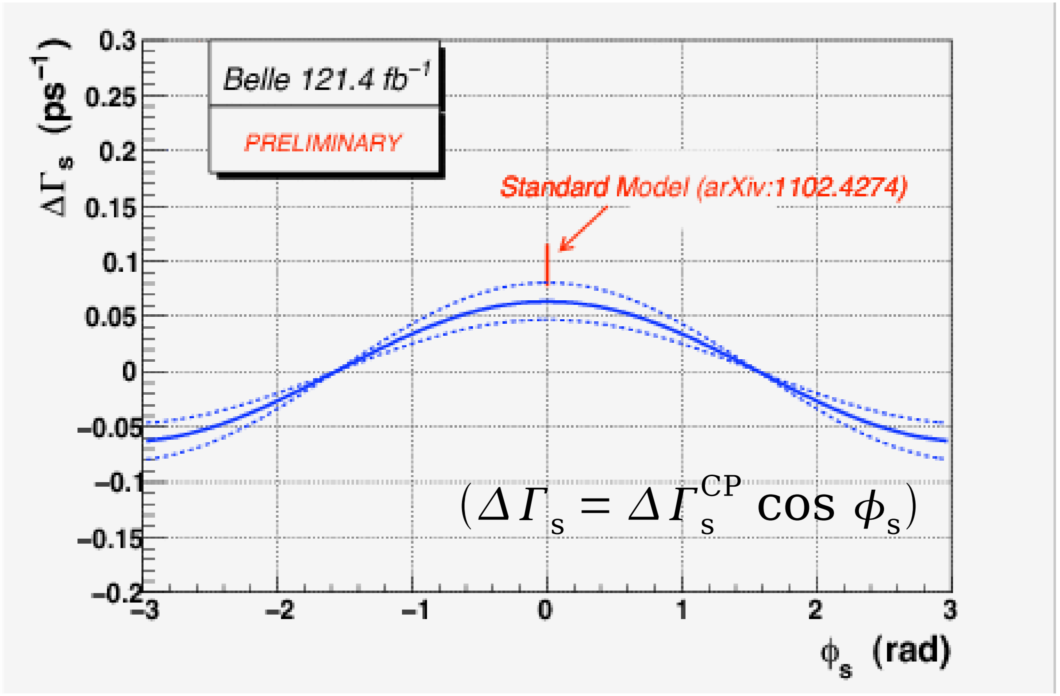


$$\mathcal{B}\,(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) = (4.3 \pm 0.4 \pm 1.0)\%$$

$$\Delta\Gamma_s / \ \Gamma_s = 2\mathcal{B} / (1 - \mathcal{B})$$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = (9.0 \pm 0.9 \pm 2.2)\%$$

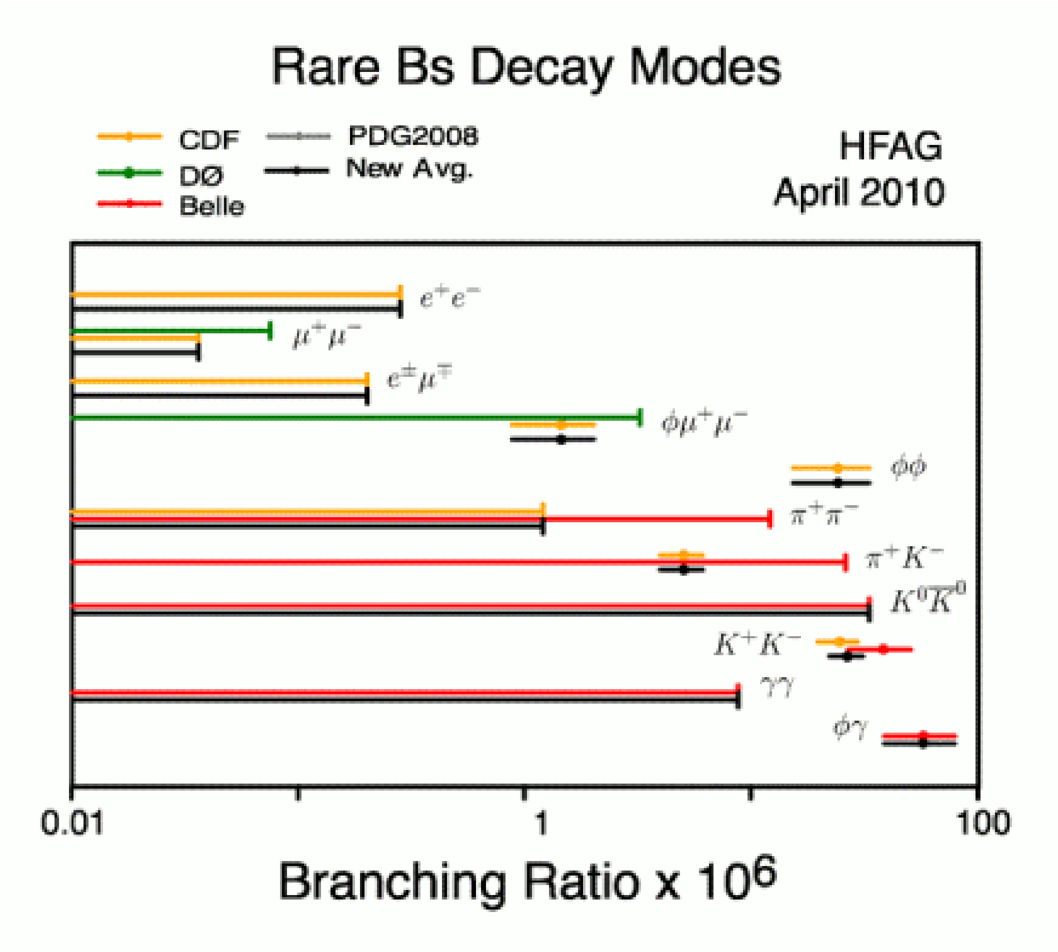
CDF: (12 ± 10)% [PRL 100, 121803]
D0: (7.2 ± 3.0)% [PRL 102, 091801]



$(\Delta\Gamma_s = \Delta\Gamma_s^{CP} \cos\phi_s)$

Rare B_s decays

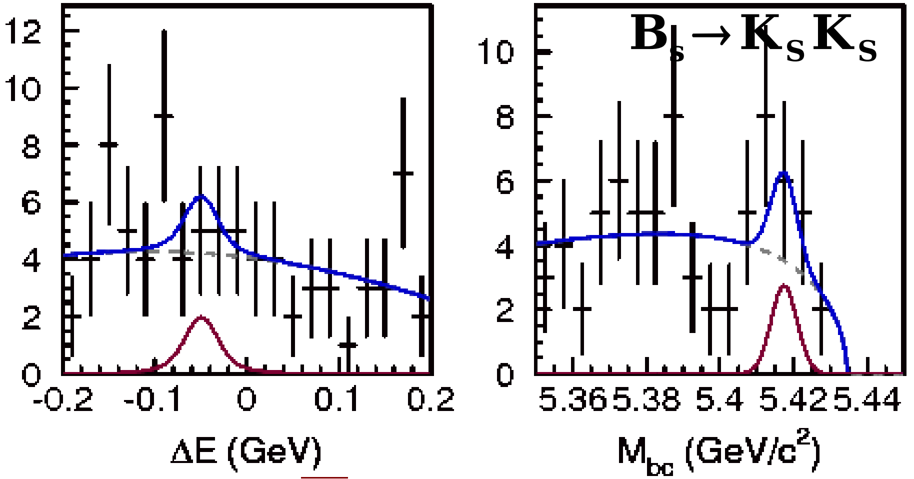
(still using 1/5 of the $\Upsilon(5S)$ data sample available)



⇒ complementarity between B-factories and LHCb

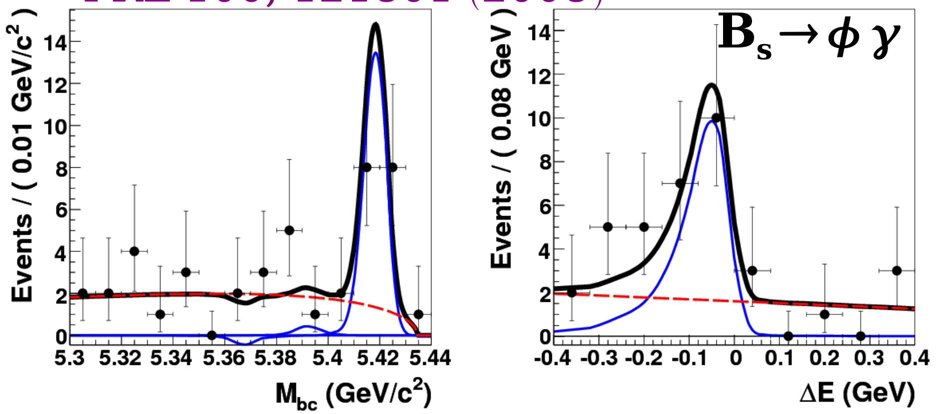
Belle can do neutrals, cleaner, but have less statistics...

arXiv:1006.5115

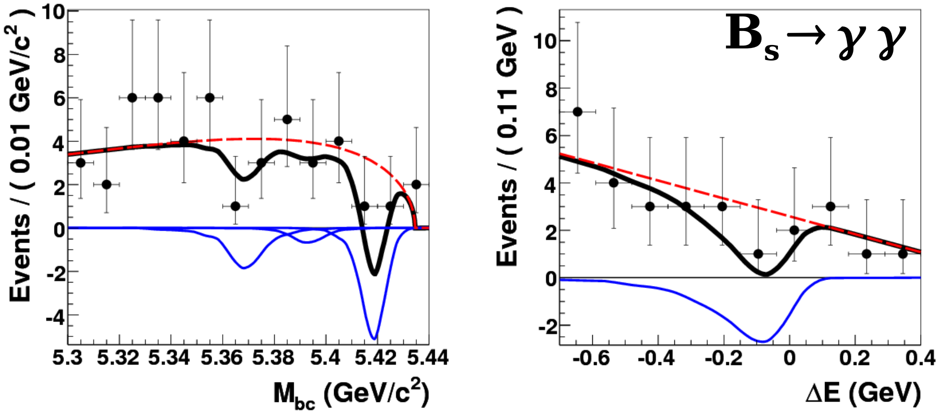


$B(B_s\to K^0\,\overline{K^0}) < 6.6\times10^{-5}$ @ 90%C.L.

PRL 100, 121801 (2008)



$\boldsymbol{B(B_s\to\phi\,\gamma) = (57^{+18}_{-15}(\text{stat})\ ^{+12}_{-11}(\text{syst}))\times10^{-6}}$



$B(B_s\to\gamma\,\gamma) < 8.7\times10^{-6}$ @ 90%C.L.

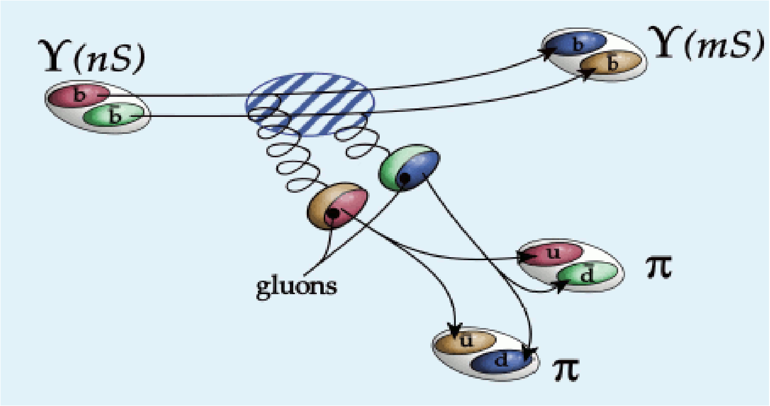
Nature of $\Upsilon(5S)$

Anomalous production of $\Upsilon(nS)\pi^+\pi^-$

PRL 100, 112001 (2008)

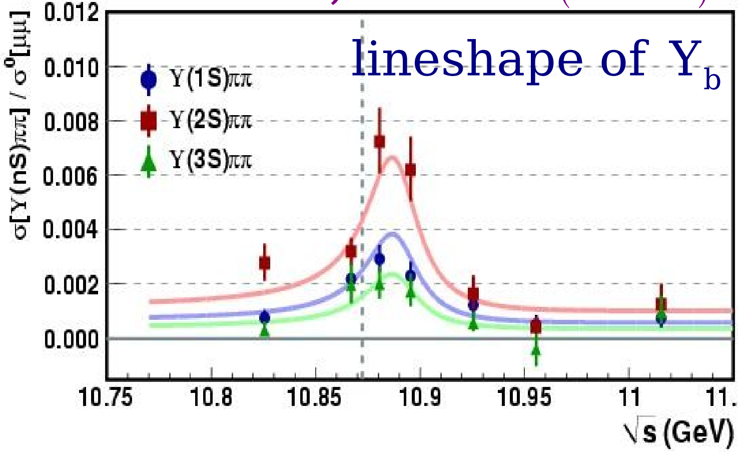
	Γ (MeV)
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(5S) \to \Upsilon(2S)\pi^+\pi^-$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(5S) \to \Upsilon(3S)\pi^+\pi^-$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.0060
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.0009
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	0.0019

$\times 10^2$



Zweig-suppressed diagram
for the transition $\Upsilon(nS) \to \Upsilon(mS)\pi^+\pi^-$

PRD 82, 091106 (2010)



1. Rescattering $\Upsilon(5S) \to BB\pi\pi \to \Upsilon(nS)\pi\pi$?

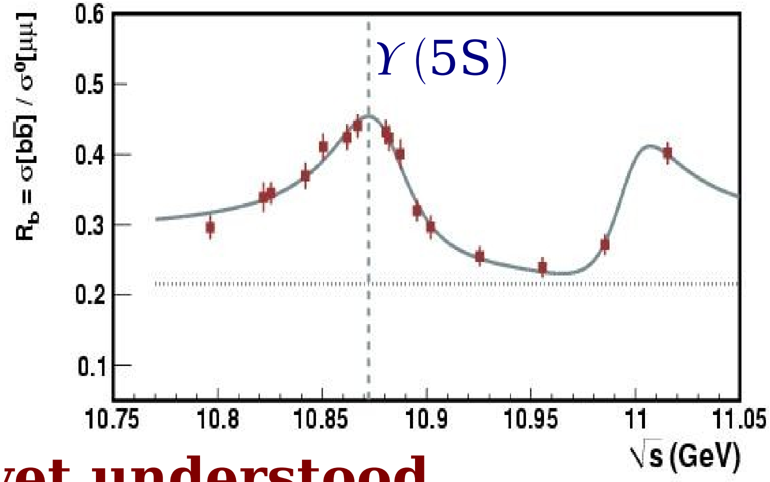
   Simonov, JETP Lett 87, 147 (2008)

2. Similar effect as in charmonium ?

   ⇒ assume a Y_b exists close to $\Upsilon(5S)$

   to distinguish them: energy scan

   ⇒ shapes of R_b and $\sigma(\Upsilon\pi\pi)$ different (only 2σ)



Nature of $\Upsilon(5S)$ is puzzling and not yet understood

Looking for $h_b(nP)$

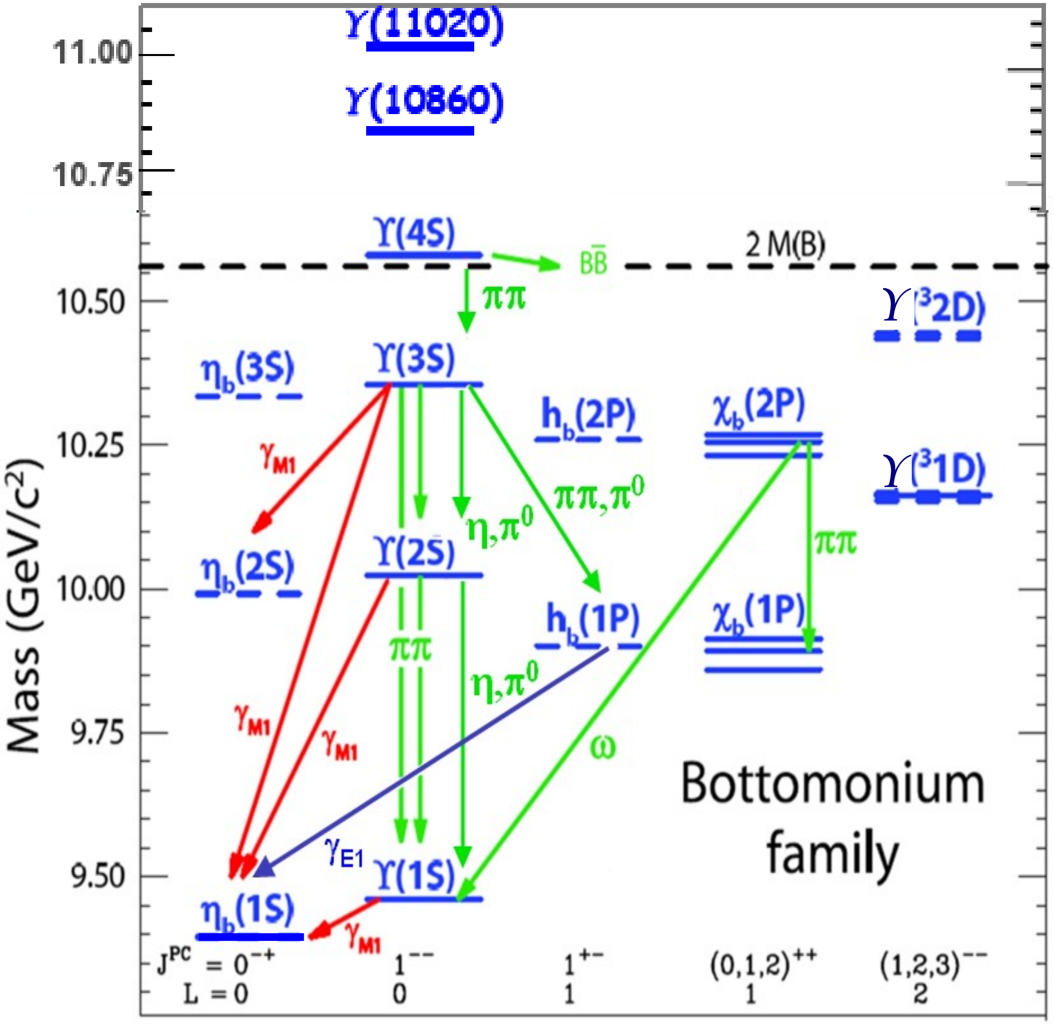
(triggered by the observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\bar{D}$ threshold by CLEO)

$(b\bar{b})$: $S=0,\ L=1,\ J^{PC}=1^{+-}$

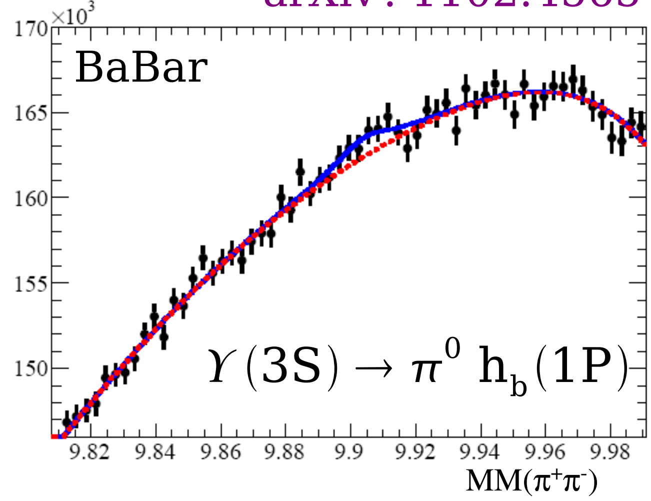
Expected mass
$\approx (M(\chi_{b0}) + 3\,M(\chi_{b1}) + 5\,M(\chi_{b2}))/9$

$\Delta M_{HF} \Rightarrow$ test of hyperfine interaction

for h_c: $\Delta M_{HF} = -0.12 \pm 0.30$ MeV,
expect smaller deviation for $h_b(nP)$

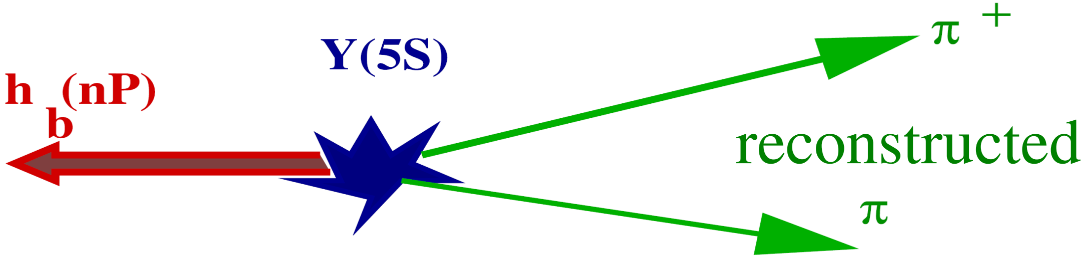


arXiv: 1102.4565



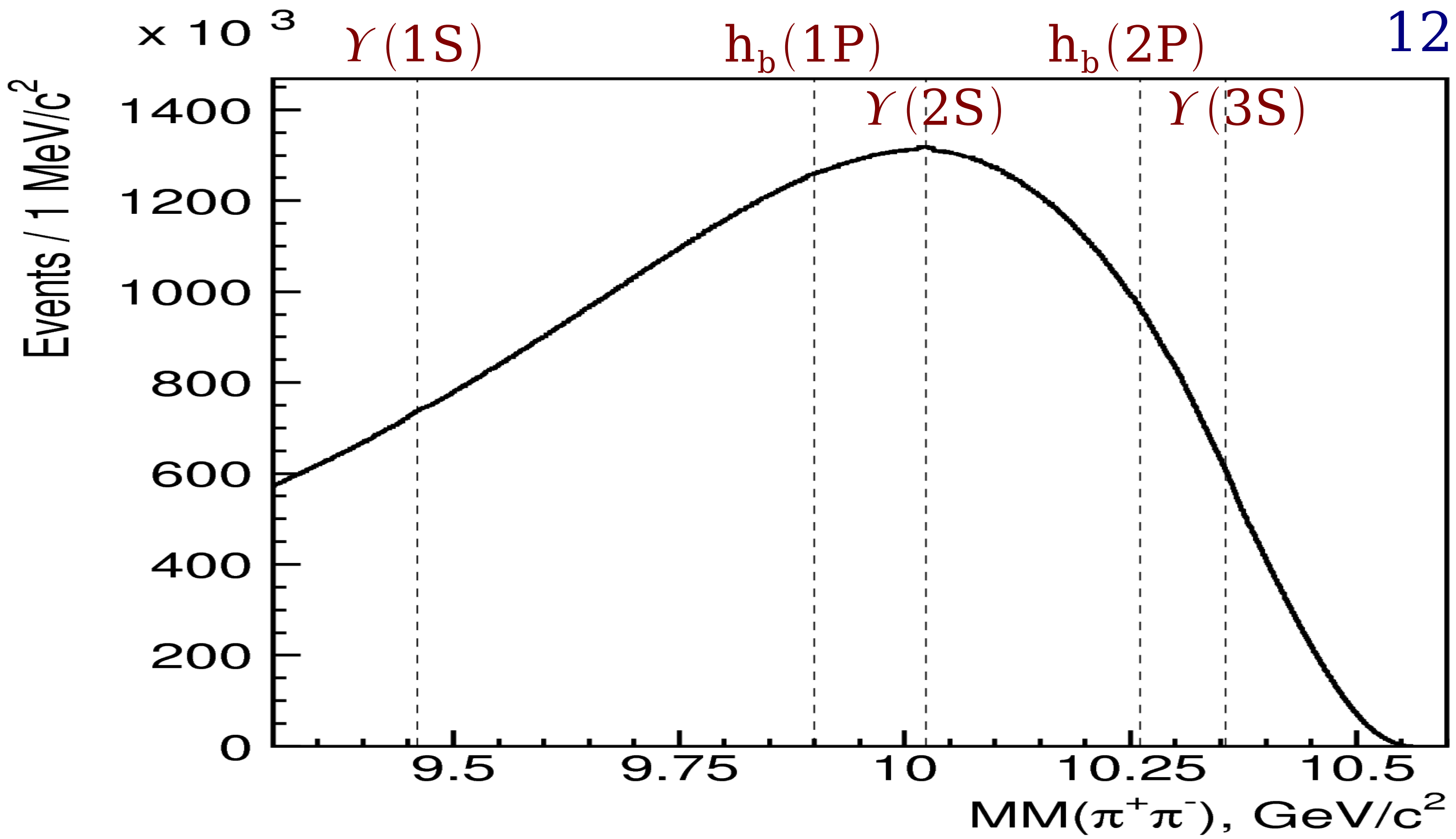
$\Upsilon(5S) \to h_b \pi^+ \pi^-$ reconstruction

$h_b \to ggg\,,\ \eta_b\,\gamma \ \Rightarrow$ no good exclusive final states



''Missing mass''

$$M(h_b) = \sqrt{(E_{CM} - E^{*}_{\pi^+\pi^-})^2 - p^{*2}_{\pi^+\pi^-}} \equiv M_{miss}(\pi^+\pi^-)$$

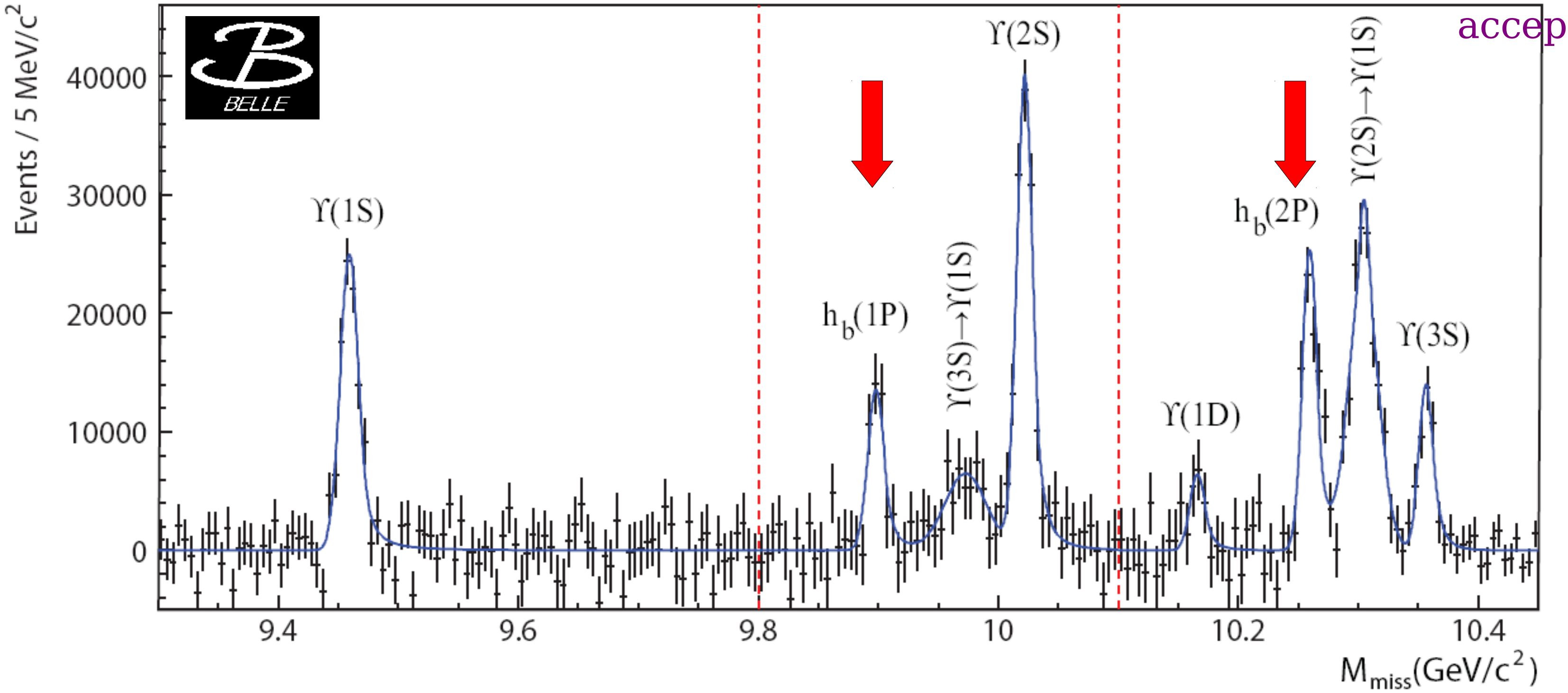


121.4 fb^{-1}

Results

$121.4\ \text{fb}^{-1}$

[arXiv:1103.3419]
accepted by PRL



	Yield, 10^3	Mass, MeV$/c^2$	Significance
$\Upsilon(1S)$	$105.0 \pm 5.8 \pm 3.0$	$9459.4 \pm 0.5 \pm 1.0$	$18.1\,\sigma$
$h_b(1P)$	$50.0 \pm 7.8^{+4.5}_{-9.1}$	$9898.2^{+1.1+1.0}_{-1.0-1.1}$	$6.1\,\sigma$
$3S \to 1S$	55 ± 19	9973.01	$2.9\,\sigma$
$\Upsilon(2S)$	$143.8 \pm 8.7 \pm 6.8$	$10022.2 \pm 0.4 \pm 1.0$	$17.1\,\sigma$
$\Upsilon(1D)$	22.4 ± 7.8	10166.1 ± 2.6	$2.4\,\sigma$
$h_b(2P)$	$84.0 \pm 6.8^{+23.}_{-10.}$	$10259.8 \pm 0.6^{+1.4}_{-1.0}$	$12.3\,\sigma$
$2S \to 1S$	$151.3 \pm 9.7^{+9.0}_{-20.}$	$10304.6 \pm 0.6 \pm 1.0$	$15.7\,\sigma$
$\Upsilon(3S)$	$45.5 \pm 5.2 \pm 5.1$	$10356.7 \pm 0.9 \pm 1.1$	$8.5\,\sigma$

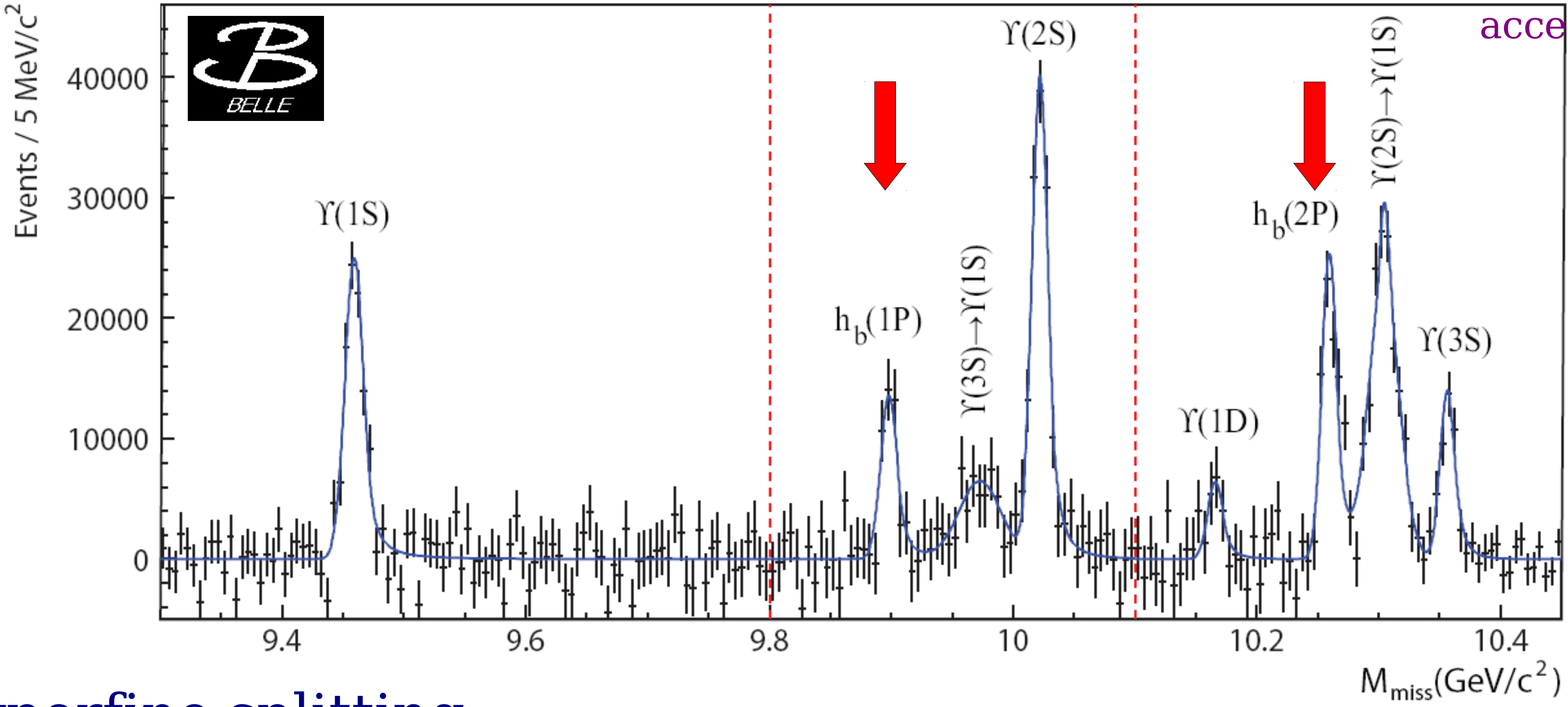
Significance
w/ systematics

$h_b(1P)$ $5.5\,\sigma$
$h_b(2P)$ $11.2\,\sigma$

Results

$121.4\ \text{fb}^{-1}$

[arXiv:1103.3419]
accepted by PRL



Hyperfine splitting

deviations from CoG of χ_{bJ} masses
consistent with zero, as expected

$(1.7 \pm 1.5)\ \text{MeV}/c^2$ for $h_b(1P)$

$(0.5\ ^{+1.6}_{-1.2})\ \text{MeV}/c^2$ for $h_b(2P)$

Ratio of production rates

splin-flip

$$\frac{\Gamma[\Upsilon(5S)\to h_b(nP)\pi^+\pi^-]}{\Gamma[\Upsilon(5S)\to \Upsilon(2S)\pi^+\pi^-]} = \begin{cases} 0.45 \pm 0.08\ ^{+0.07}_{-0.12} & \text{for } h_b(1P) \\ 0.77 \pm 0.08\ ^{+0.22}_{-0.17} & \text{for } h_b(2P) \end{cases}$$

no splin-flip

supposed to be suppressed
by $1/m_b$ in the amplitude

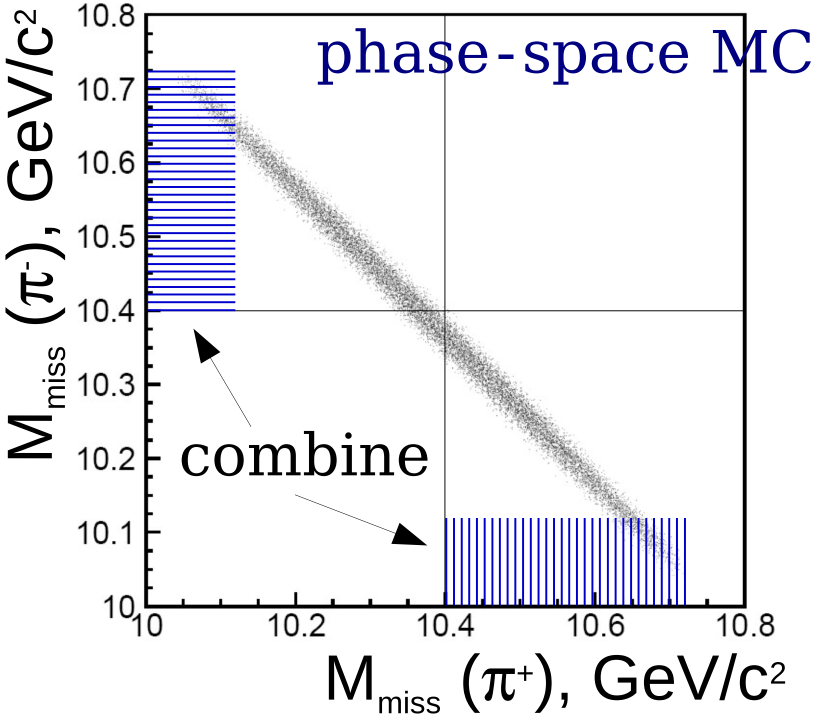
Mechanism of $\Upsilon(5S)\to h_b(nP)\pi^+\pi^-$ decay seems exotic ! [arXiv:1108.2197]

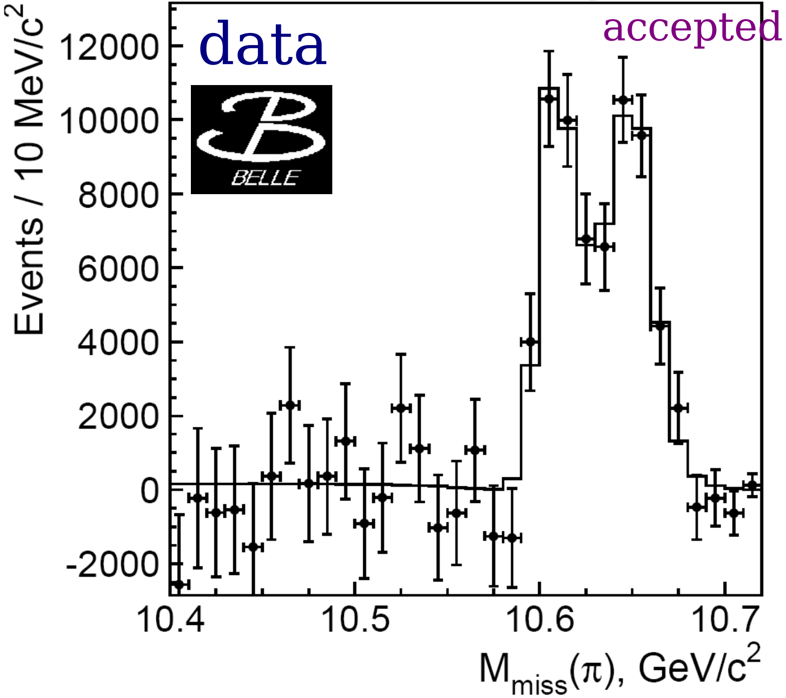
Resonant structure of $\Upsilon(5S) \to h_b(1P)\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

$121.4\ fb^{-1}$

[arXiv:1110.2251]
accepted by PRL





Fit function $$|BW(s, M_1, \Gamma_1) + a e^{i\phi} BW(s, M_2, \Gamma_2) + b e^{i\psi}|^2 \frac{qp}{\sqrt{s}}$$

Results

$M_1 = 10605 \pm 2\ ^{+3}_{-1}\ MeV/c^2$ $\sim B\overline{B}^*$ threshold

$\Gamma_1 = 11.4\ ^{+4.5}_{-3.9}\ ^{+2.1}_{-1.2}\ MeV$ $a = 1.39 \pm 0.37\ ^{+0.05}_{-0.15}$

$M_2 = 10654 \pm 3\ ^{+1}_{-2}\ MeV/c^2$ $\sim B\overline{B}^*$ threshold

$\Gamma_2 = 20.9\ ^{+5.4}_{-4.7}\ ^{+2.1}_{-5.7}\ MeV$ $\phi = (187\ ^{+44}_{-57}\ ^{+3}_{-12})^\circ$

Significances

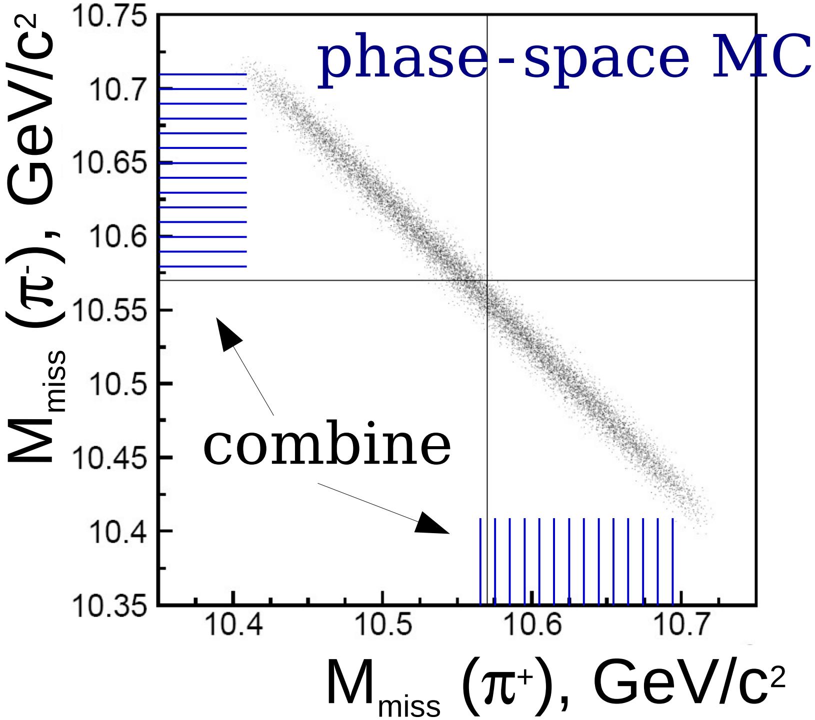
18σ (16σ w/syst)

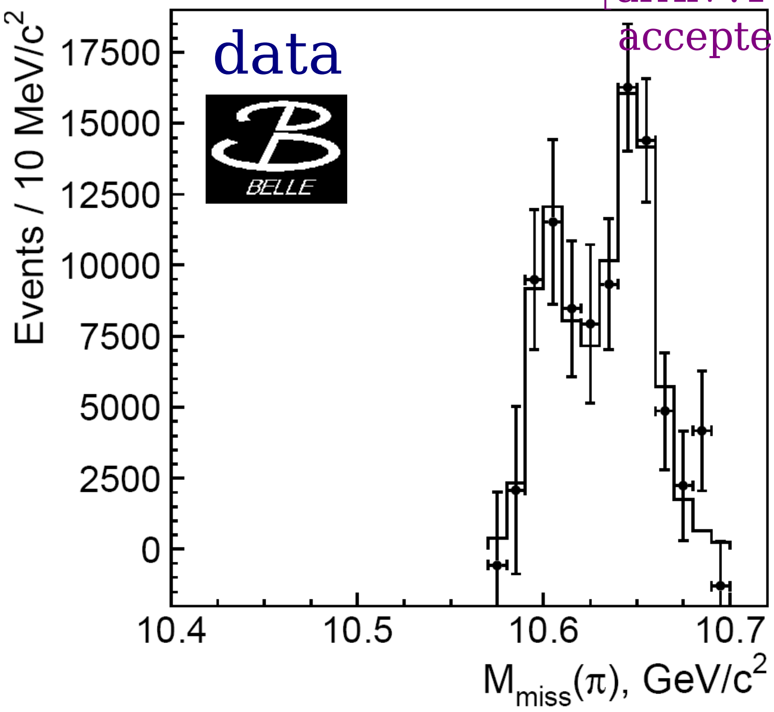
Resonant structure of $\Upsilon(5S) \to h_b(2P)\pi^+\pi^-$

$M(h_b\pi^+) \equiv M_{miss}(\pi^-)$

$121.4\ \mathrm{fb}^{-1}$

[arXiv:1110.2251]
accepted by PRL





$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$ (consistent)
$M_1 = 10605 \pm 2\ ^{+3}_{-1}$ MeV/c^2	$10599\ ^{+6}_{-3}\ ^{+5}_{-4}$ MeV/c^2
$\Gamma_1 = 11.4\ ^{+4.5}_{-3.9}\ ^{+2.1}_{-1.2}$ MeV	$13\ ^{+10}_{-8}\ ^{+9}_{-7}$ MeV
$M_2 = 10654 \pm 3\ ^{+1}_{-2}$ MeV/c^2	$10651\ ^{+2}_{-3}\ ^{+3}_{-2}$ MeV/c^2
$\Gamma_2 = 20.9\ ^{+5.4}_{-4.7}\ ^{+2.1}_{-5.7}$ MeV	$19 \pm 7\ ^{+11}_{-7}$ MeV
$a = 1.39 \pm 0.37\ ^{+0.05}_{-0.15}$	$1.6\ ^{+0.6}_{-0.4}\ ^{+0.4}_{-0.6}$
$\phi = (187\ ^{+44}_{-57}\ ^{+3}_{-12})^\circ$	$(181\ ^{+65}_{-105}\ ^{+74}_{-109})^\circ$

Significances

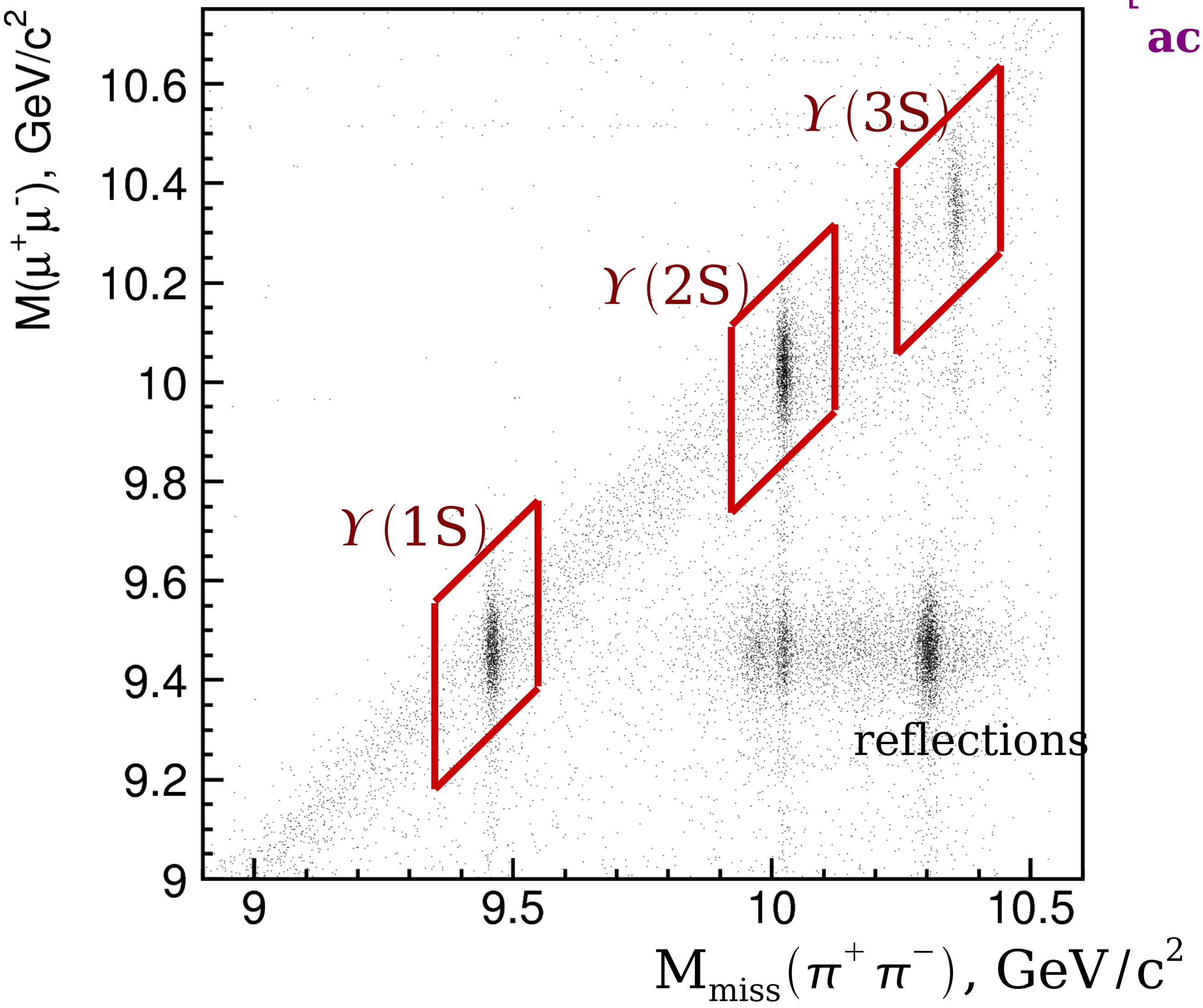
6.7σ (5.6σ w/syst)

…and what about $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ final state ?

$(n = 1, 2, 3)$

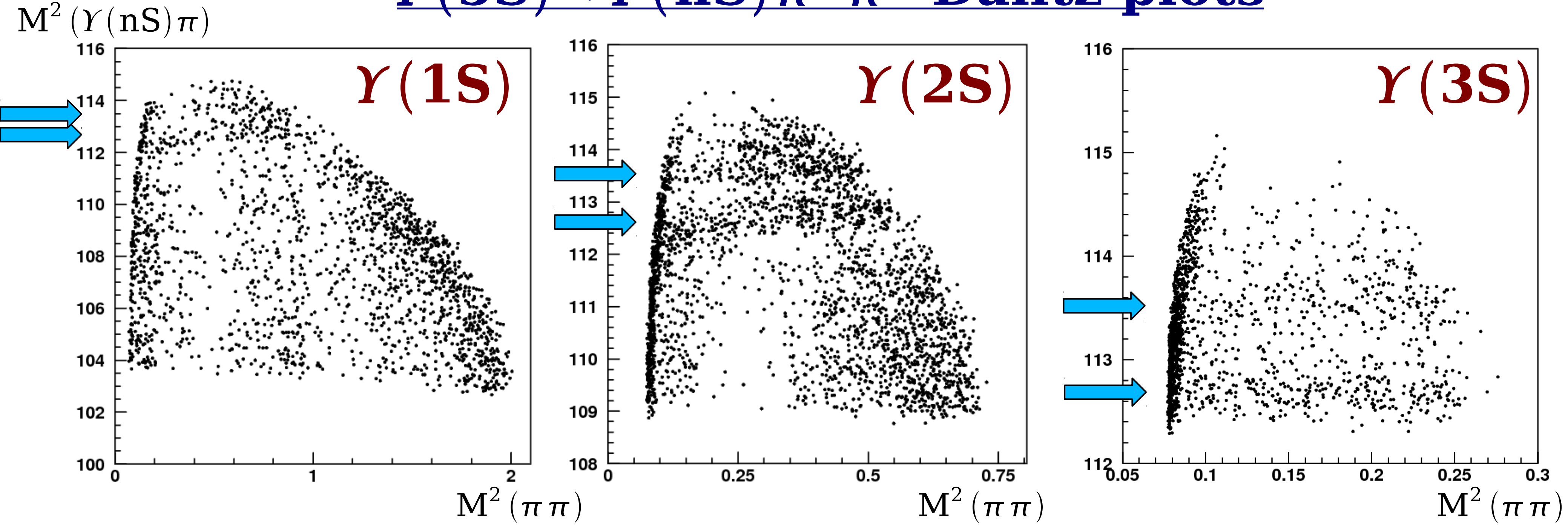
121.4 fb^{-1}

[arXiv:1110.2251]
accepted by PRL



Note: here $\Upsilon(nS)$ is reconstructed in the $\mu^+\mu^-$ channel !!

$\Upsilon(5S)\rightarrow\Upsilon(nS)\pi^+\pi^-$ Dalitz plots



⇒ two resonances

⇒ clear signs of interference ⇒ amplitude analysis is required

Signal amplitude parameterization:

Flatte

$$S(s_1, s_2) = A(Z_{b1}) + A(Z_{b2}) + A(f_0(980)) + A(f_2(1275)) + A_{NR}$$

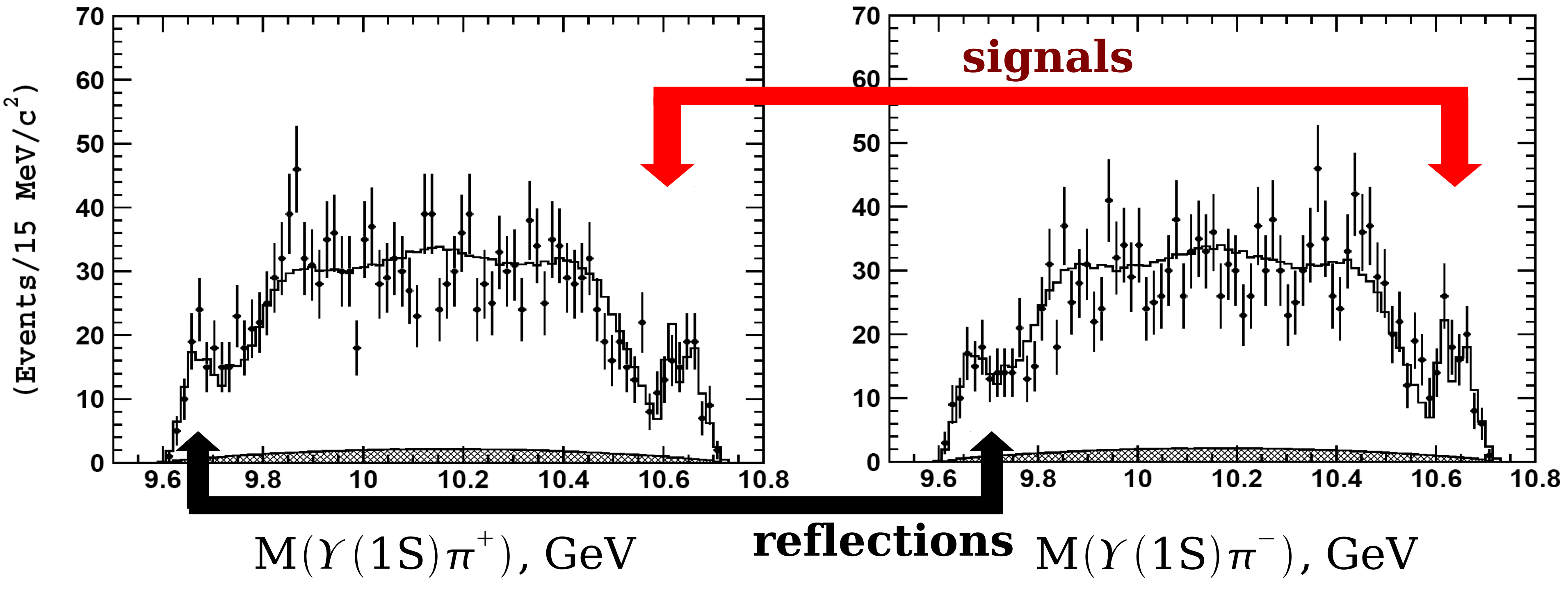
Breit-Wigner

$$A_{NR} = C_1 + C_2 \, . \, m^2(\pi\pi)$$

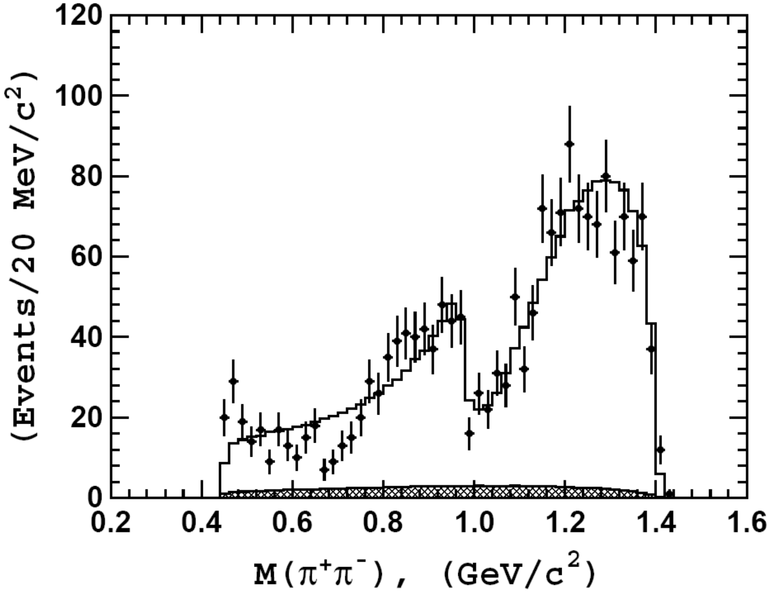
Parameterization of the non-resonant amplitude as discussed in:

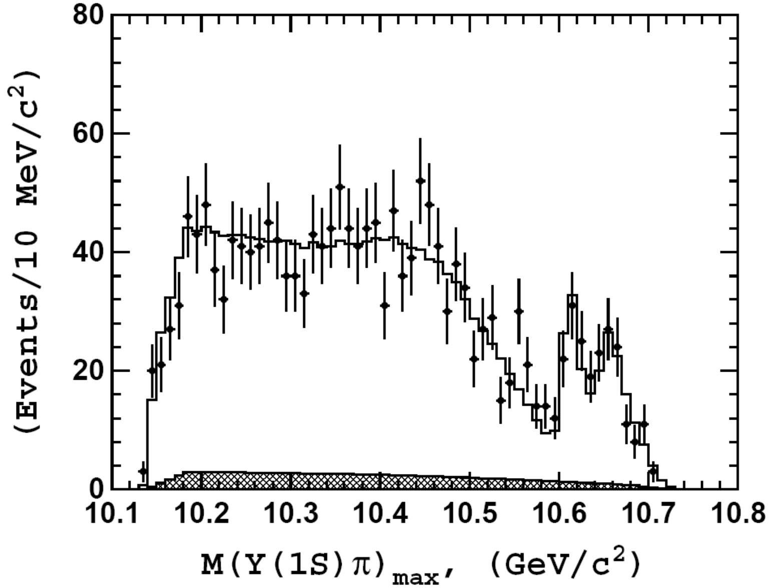
[1] M.B.Voloshin, Prog. Part. Nucl. Phys. 61:455, 2008
[2] M.B.Voloshin, Phys. Rev. D74:054022, 2006

Results: $\Upsilon(1S)\pi^+\pi^-$

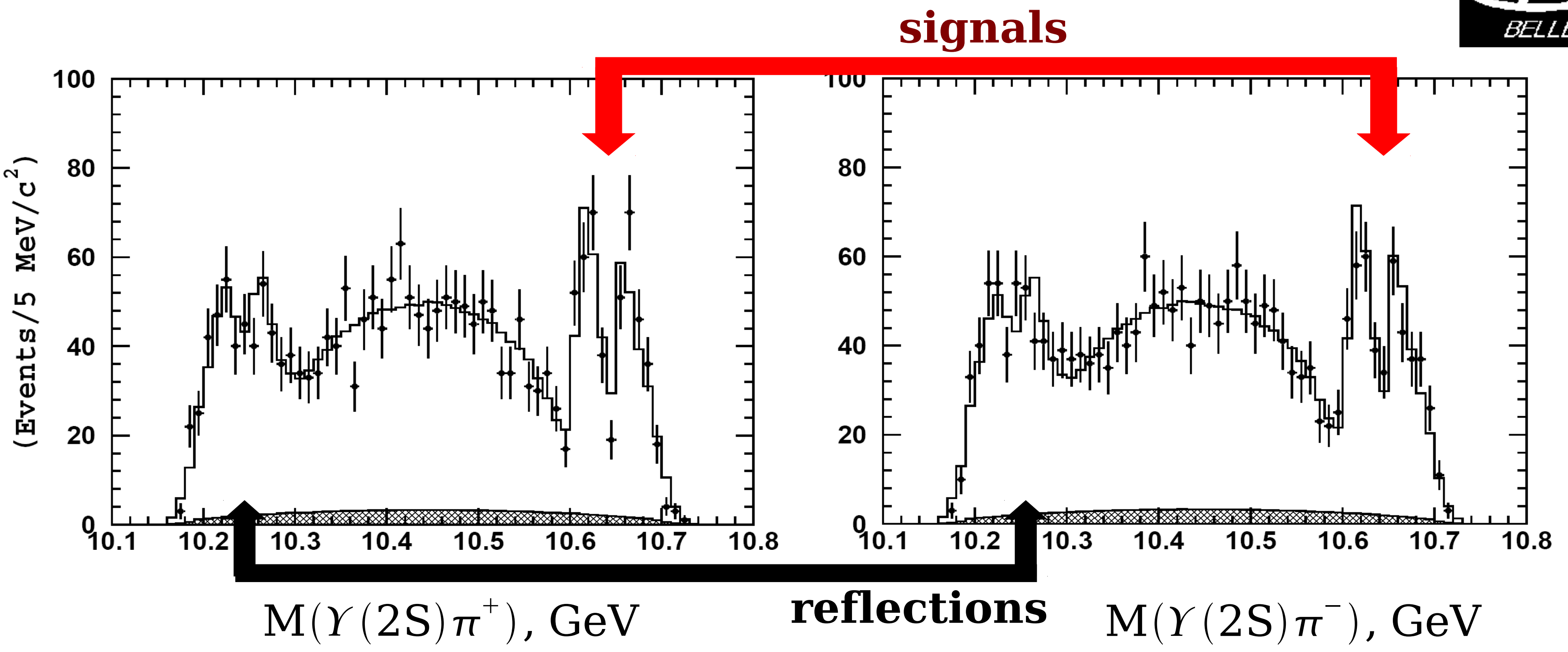

signals

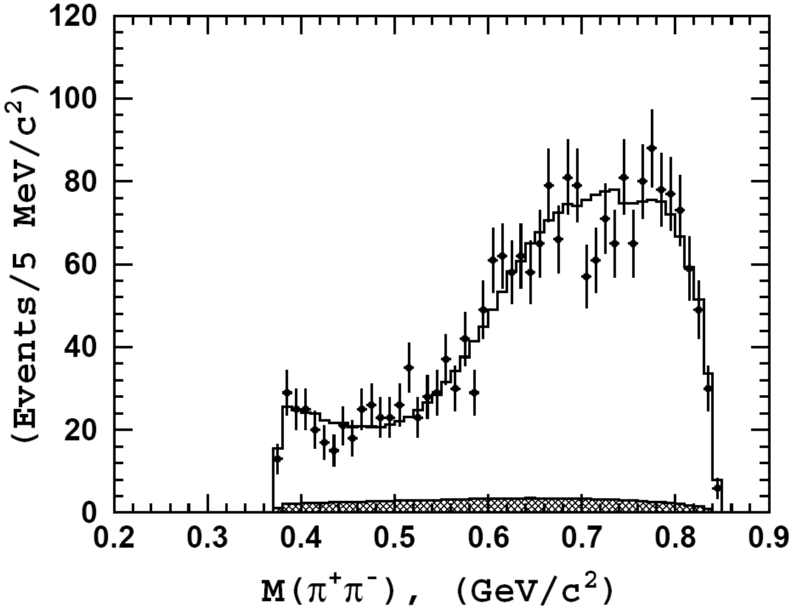
reflections

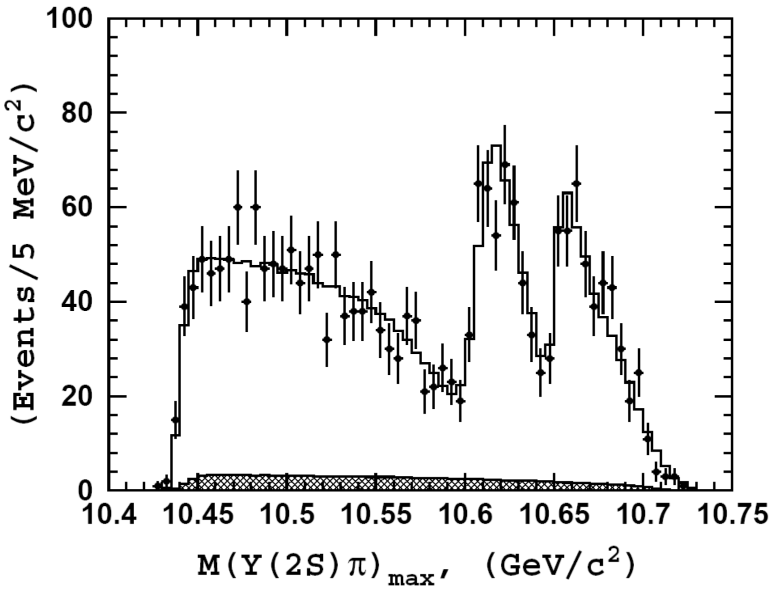




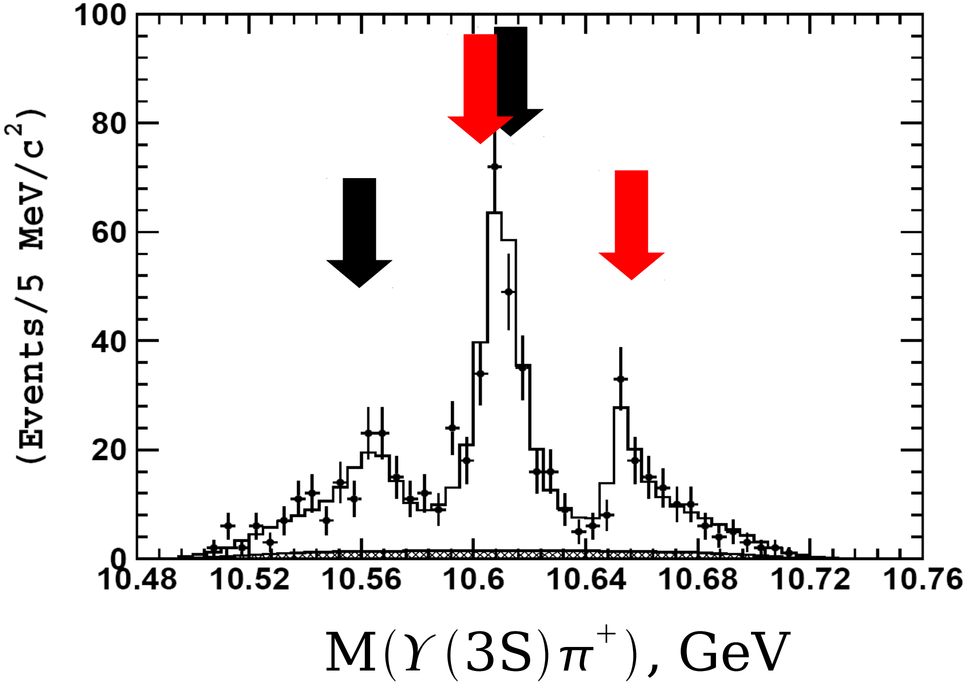
Results: $\Upsilon(2S)\pi^+\pi^-$

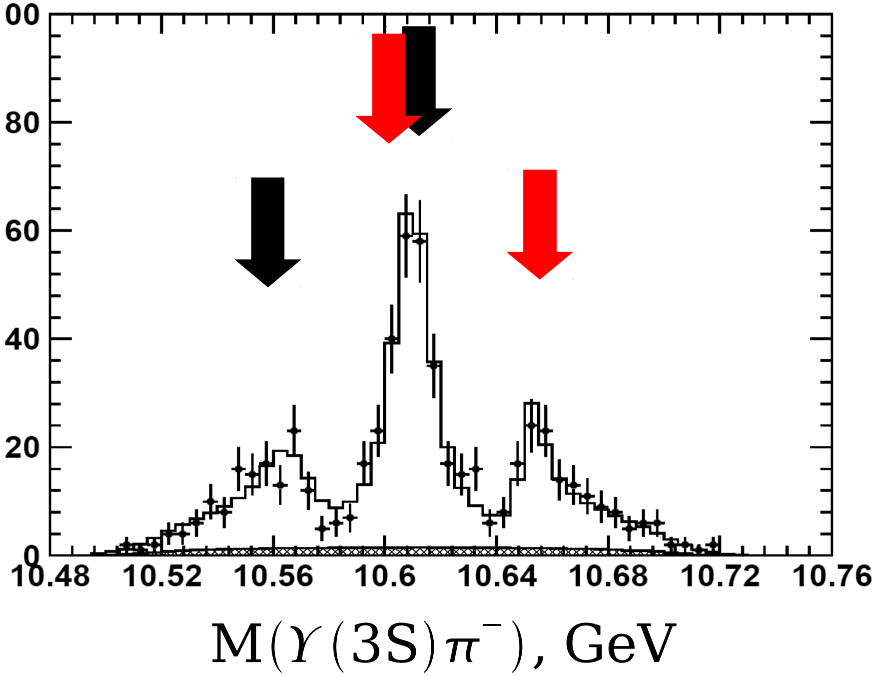


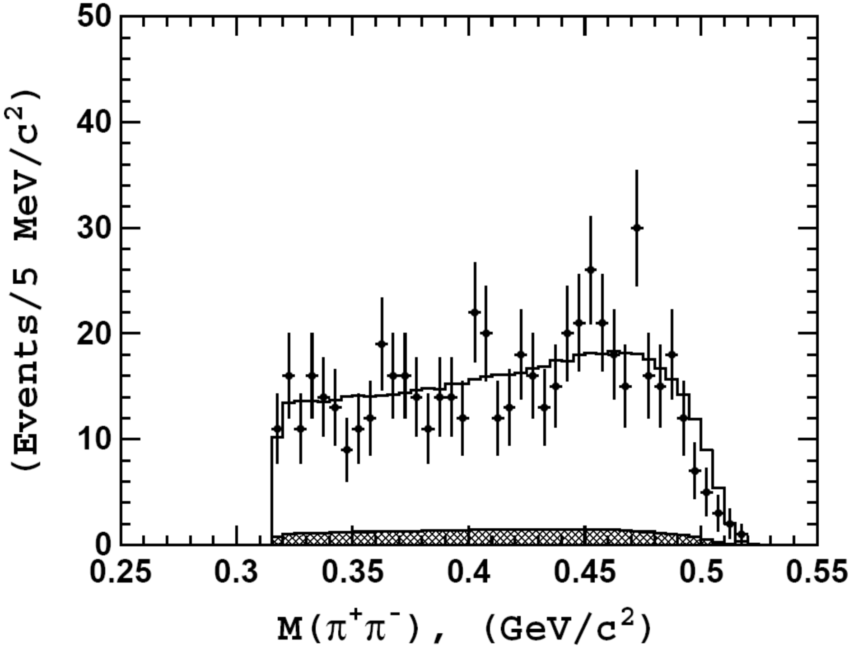


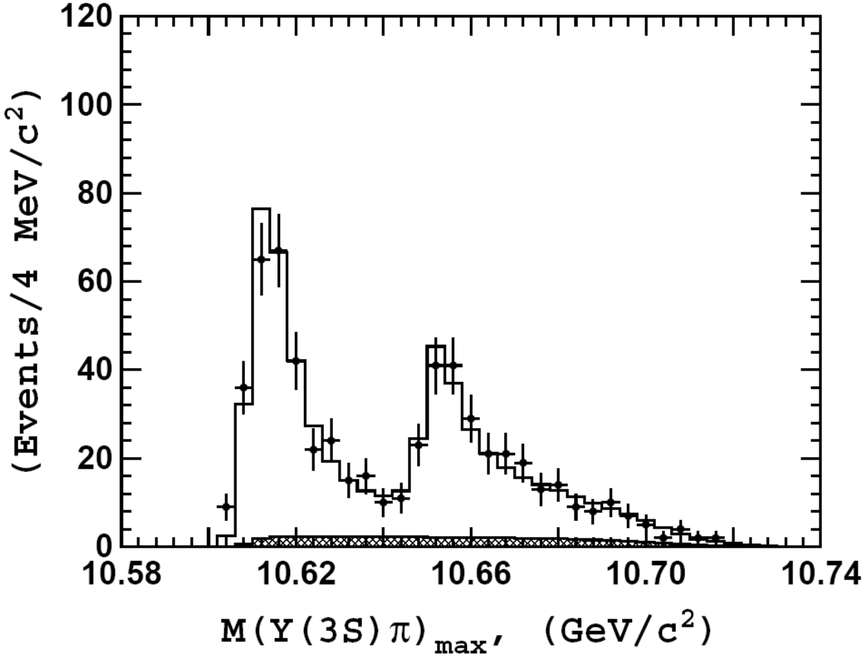


Results: $\Upsilon(3S)\pi^+\pi^-$



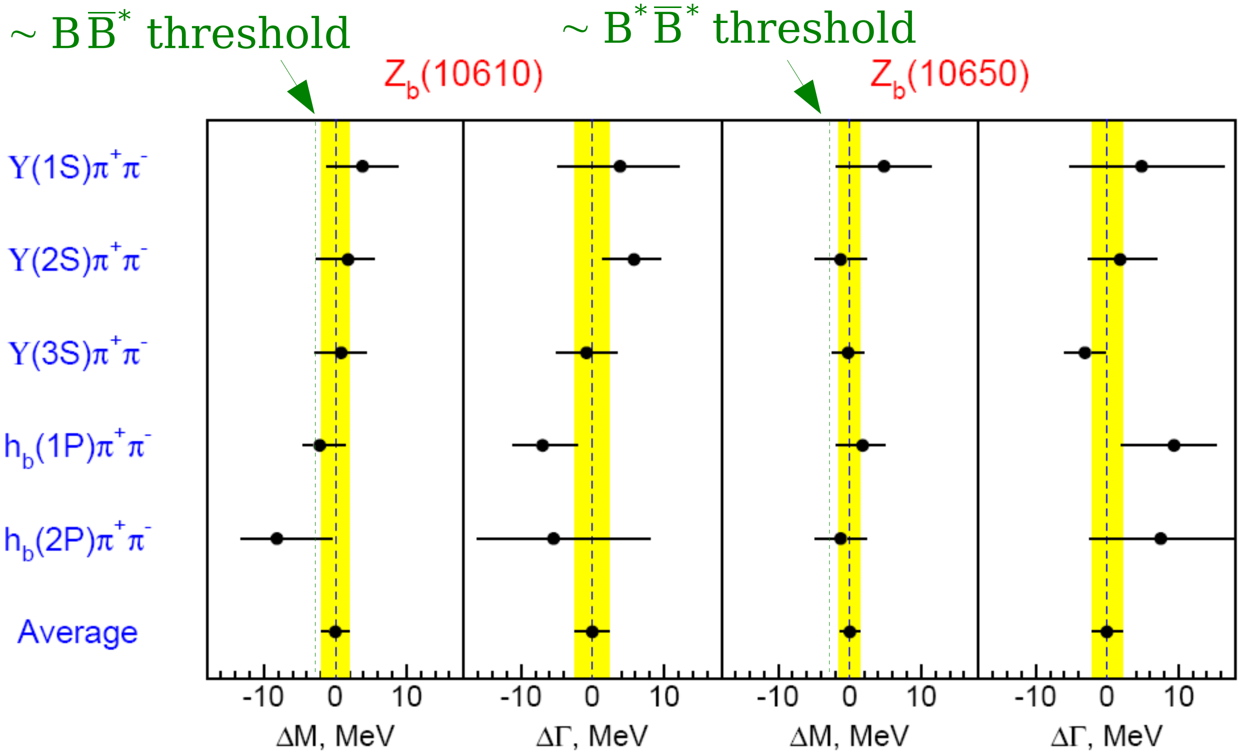






Summary of parameters of charged Z_b states

[arXiv:1110.2251]



$Z_b(10610)$

$M = 10607.2 \pm 2.0$ MeV

$\Gamma = 18.4 \pm 2.4$ MeV

$Z_b(10650)$

$M = 10652.2 \pm 1.5$ MeV

$\Gamma = 11.5 \pm 2.2$ MeV

Final state	$\Upsilon(1S)\pi^+\pi^-$	$\Upsilon(2S)\pi^+\pi^-$	$\Upsilon(3S)\pi^+\pi^-$	$h_b(1P)\pi^+\pi^-$	$h_b(2P)\pi^+\pi^-$
$M[Z_b(10610)]$, MeV/c^2	$10611 \pm 4 \pm 3$	$10609 \pm 2 \pm 3$	$10608 \pm 2 \pm 3$	$10605 \pm 2^{+3}_{-1}$	10599^{+6+5}_{-3-4}
$\Gamma[Z_b(10610)]$, MeV	$22.3 \pm 7.7^{+3.0}_{-4.0}$	$24.2 \pm 3.1^{+2.0}_{-3.0}$	$17.6 \pm 3.0 \pm 3.0$	$11.4\,^{+4.5+2.1}_{-3.9-1.2}$	$13\,^{+10+9}_{-8-7}$
$M[Z_b(10650)]$, MeV/c^2	$10657 \pm 6 \pm 3$	$10651 \pm 2 \pm 3$	$10652 \pm 1 \pm 2$	$10654 \pm 3\,^{+1}_{-2}$	10651^{+2+3}_{-3-2}
$\Gamma[Z_b(10650)]$, MeV	$16.3 \pm 9.8^{+6.0}_{-2.0}$	$13.3 \pm 3.3^{+4.0}_{-3.0}$	$8.4 \pm 2.0 \pm 2.0$	$20.9\,^{+5.4+2.1}_{-4.7-5.7}$	$19 \pm 7\,^{+11}_{-7}$
Rel. normalization	$0.57 \pm 0.21^{+0.19}_{-0.04}$	$0.86 \pm 0.11^{+0.04}_{-0.10}$	$0.96 \pm 0.14^{+0.08}_{-0.05}$	$1.39 \pm 0.37^{+0.05}_{-0.15}$	$1.6^{+0.6+0.4}_{-0.4-0.6}$
Rel. phase, degrees	$58 \pm 43^{+4}_{-9}$	$-13 \pm 13^{+17}_{-8}$	$-9 \pm 19^{+11}_{-26}$	187^{+44+3}_{-57-12}	$181^{+65+74}_{-105-109}$

- Masses and width are consistent
- Relative yield of $Z_b(10610)$ and $Z_b(10650)$ ~ 1
- Relative phases are swapped for Υ and h_b final states

and more…

Expected decays of h_b

[Godfrey & Rosner, PRD 66, 014012 (2002)]

$h_b(1P) \to ggg\ (57\%),\ \eta_b(1S)\gamma\ (41\%),\ \gamma gg\ (2\%)$

$h_b(2P) \to ggg\ (63\%),\ \eta_b(1S)\gamma\ (13\%),\ \eta_b(2S)\gamma\ (19\%),\ \gamma gg\ (2\%)$

and Belle recently observed large yields of $h_b(1P)$ and $h_b(2P)$!

opportunity to study $\eta_b(nS)$ states…

Experimental status of η_b

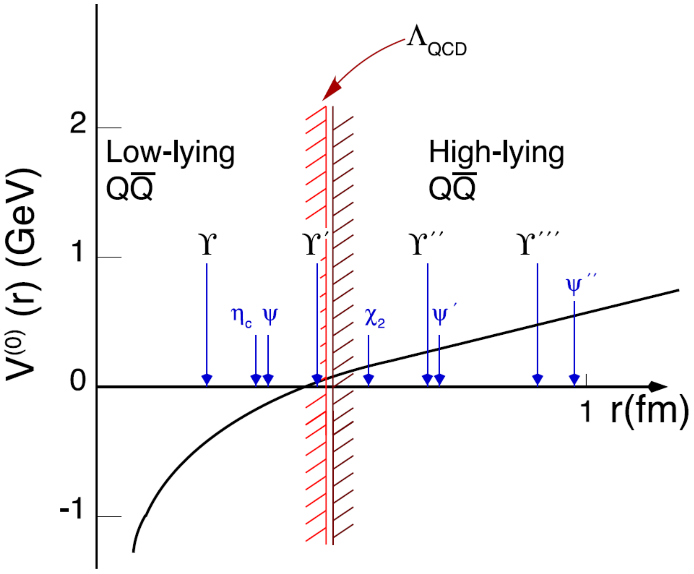
$M[\eta_b(1S)] = 9390.9 \pm 2.8$ MeV (BaBar + CLEO)

$M[\Upsilon(1S)] - M[\eta_b(1S)] = 69.3\ \pm 2.8$ MeV

pNRQCD: 41 ± 14 MeV
[Kniehl et al., PRL 92, 242001 (2004)]

Lattice: 60 ± 8 MeV
[Meinel, PRD 82, 114502 (2010)]

η_b – small radius system,
precise calculation of mass



Method

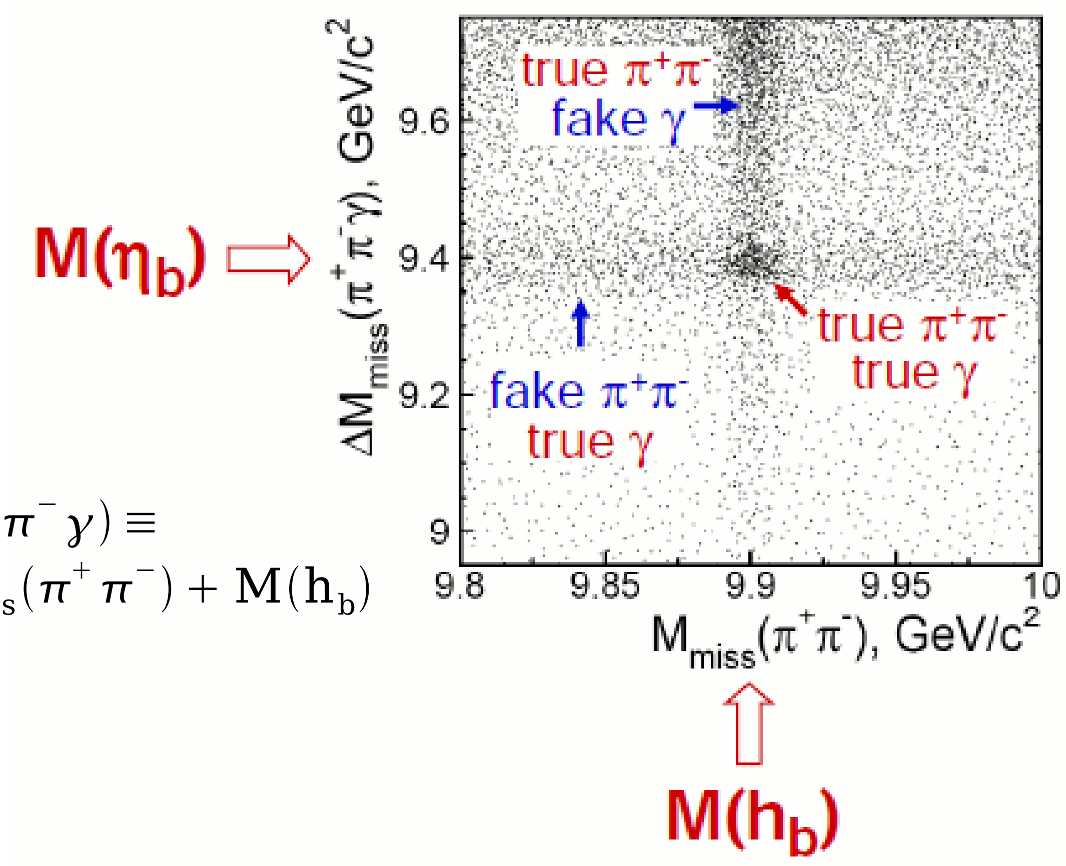
Decay chain:

$\Upsilon(5S) \to Z_b^+ \pi^-$

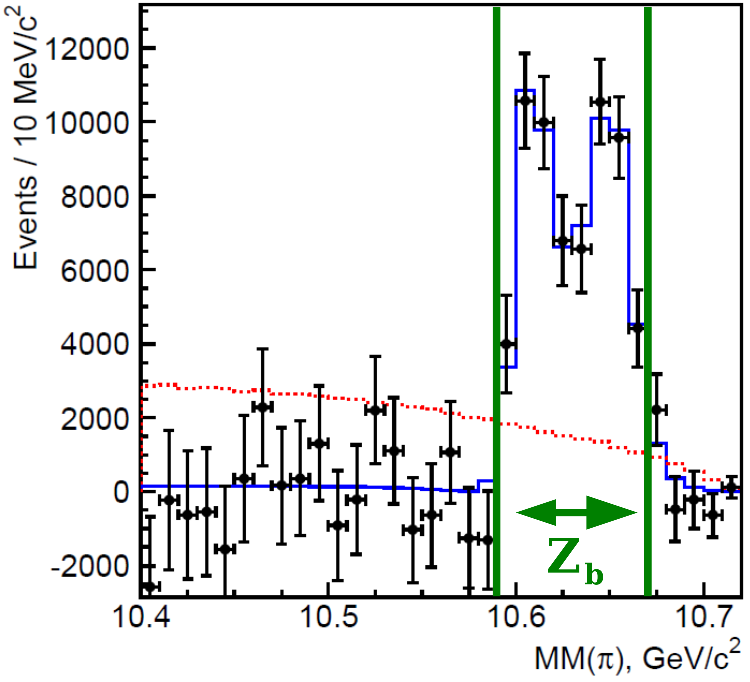
$\quad \hookrightarrow h_b(nP)\, \pi^+$

$\qquad \hookrightarrow \eta_b(mS)\, \gamma$

MC simulation



$$\Delta M_{miss}(\pi^+\pi^-\gamma) \equiv$$
$$M_{miss}(\pi^+\pi^-\gamma) - M_{miss}(\pi^+\pi^-) + M(h_b)$$



Require intermediate Z_b:

$$10.59 < MM(\pi) < 10.67 \text{ GeV}$$

bg. suppression × 5.2

approach:

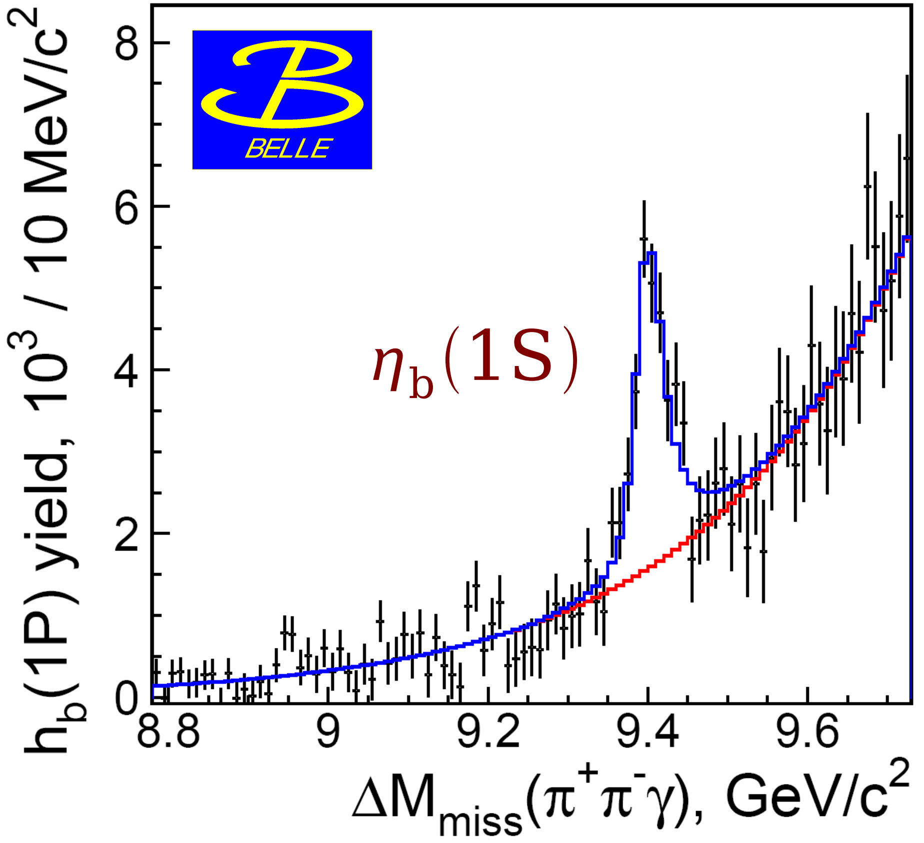
fit $M_{miss}(\pi^+\pi^-)$ spectra

in $\Delta M_{miss}(\pi^+\pi^-\gamma)$ bins

Results

arXiv : 1110.3934

non - relativistic BW ⊗ resolution + exponential func.

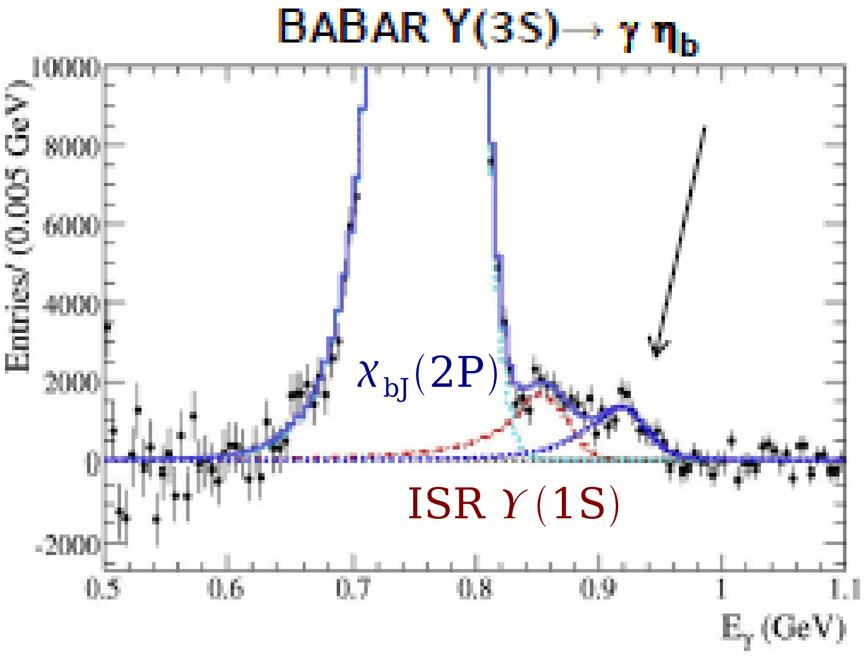


$$N[\eta_b(1S)] = (21.9 \pm 2.0 \ ^{+5.6}_{-1.7}) \times 10^3$$

$$M[\eta_b(1S)] = (9401.0 \pm 1.9 \ ^{+1.4}_{-2.4}) \text{ MeV}/c^2$$

$$\Gamma[\eta_b(1S)] = (12.4 \ ^{+5.5}_{-4.6} \ ^{+11.5}_{-3.4}) \text{ MeV}$$

$$B\,[h_b(1P) \to \eta_b(1S)\gamma] = (49.8 \pm 6.8 \ ^{+10.9}_{-5.2})\,\%$$



Hyperfine splitting

$$\Delta M_{HF}[\eta_b(1S)] = 59.3 \pm 1.9 \ ^{+2.4}_{-1.4} \text{ MeV}/c^2$$

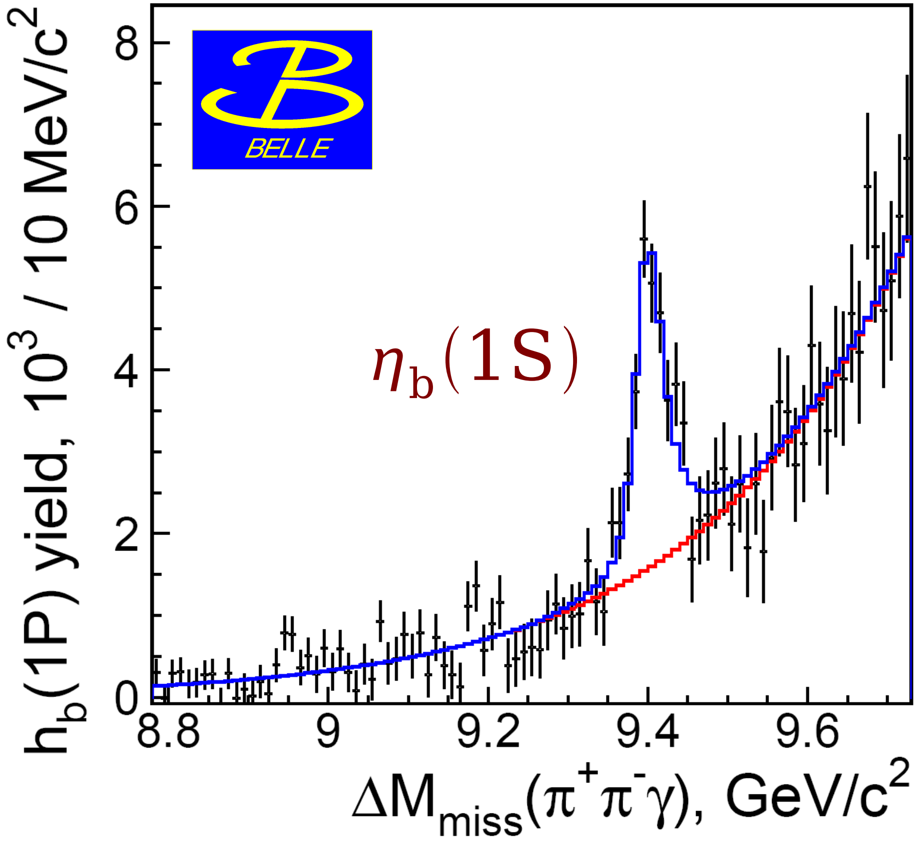
single most precise
measurement of $\eta_b(1S)$ mass

⇒ radiative decays of $h_b(2P)$, search for $\eta_b(2S)$ coming...

Results

arXiv : 1110.3934

non-relativistic BW ⊗ resolution + exponential func.



$$N[\eta_b(1S)] = (21.9 \pm 2.0\ ^{+5.6}_{-1.7}) \times 10^3$$

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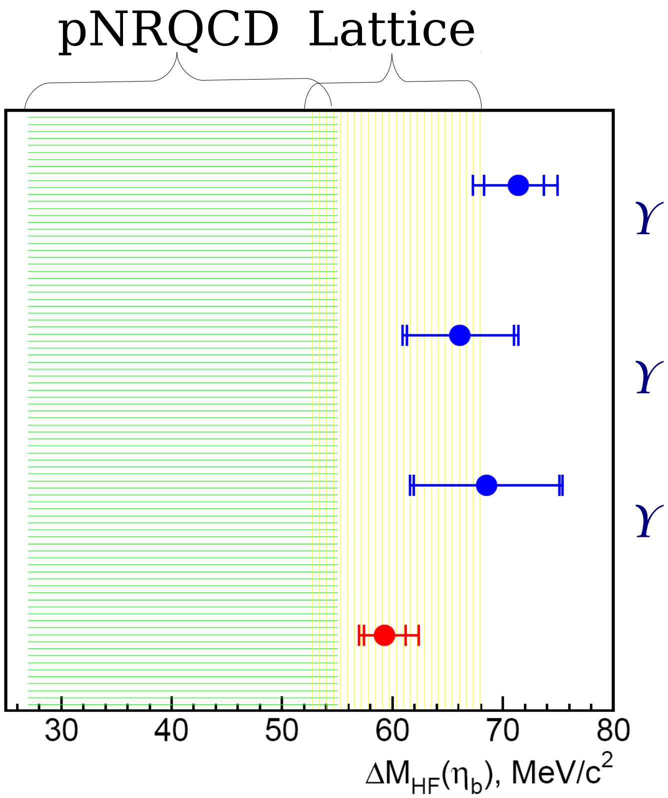


BaBar
$\Upsilon(3S) \to \eta_b(1S)\gamma$

BaBar
$\Upsilon(2S) \to \eta_b(1S)\gamma$

CLEO
$\Upsilon(3S) \to \eta_b(1S)\gamma$

Belle
preliminary

Hyperfine splitting
$\Delta M_{HF}[\eta_b(1S)] = 59.3 \pm 1.9\ ^{+2.4}_{-1.4}\ \mathrm{MeV}/c^2$

single most precise
measurement of $\eta_b(1S)$ mass

⇒ radiative decays of $h_b(2P)$, search for $\eta_b(2S)$ coming...

Summary

Exciting new results in 2011 :

⇒ new (updated) measurements for the UT angles β, γ

⇒ new results with full $\Upsilon(5S)$ data sample
(B_s decays but also bottomonium studies)

Final Belle data sample is yet to be fully analyzed !

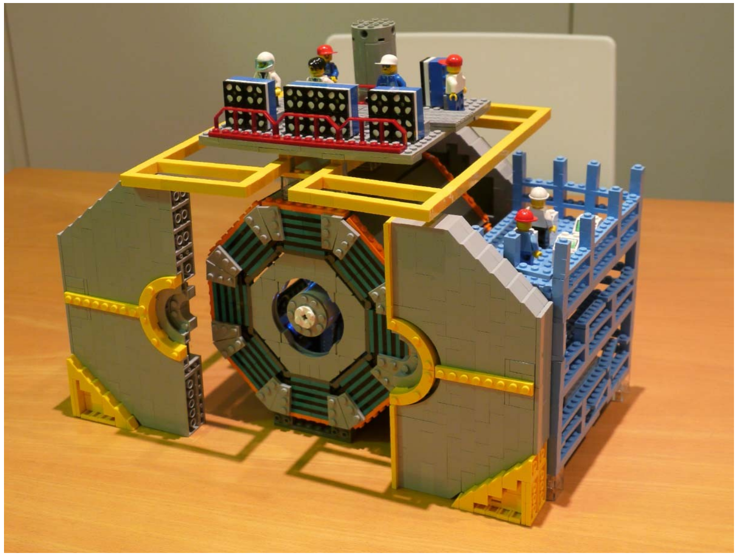
- **more on α ($\pi^0\pi^0$, $\rho^+\rho^0$), γ...**
- **Rare B decays: $K^{(*)}\nu\bar{\nu}$, $\tau\nu$, $\mu\nu$, $\gamma\gamma$, ...**
- **Results on B_s decays with 5 × more stat**
- **τ physics (lifetime, LVF decays), charm (mixing $K\pi$, KK, $K_S\pi\pi$), new particles (X, Y, Z), bottomonium...**

and then...

and then…

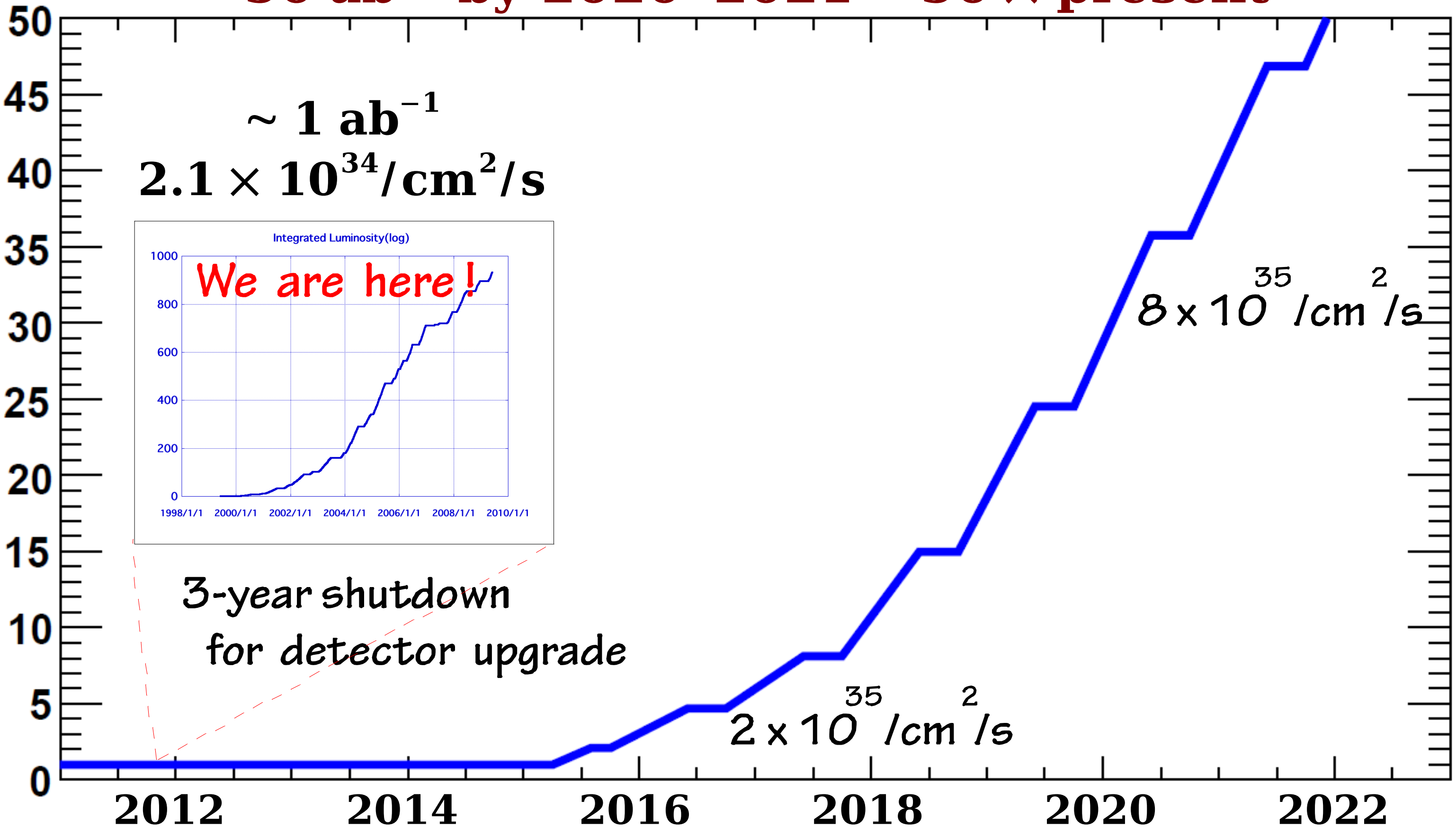
⇒ physics with O(10^{10}) B, τ, D….

SuperKEKB/Belle II (in Japan)



⇒ KEKB upgrade has been approved

50 ab^{-1} by 2020-2021 = 50 × present



Search for $\mathbf{B_s^0 \to J/\psi\, f_0(980)}$

Contribution to FPCP 2010 (arXiv:1009.2605)

- Silver mode at LHCb to measure β_s (CP-violating phase in the B_s mixing)
- BR is smaller than $B_s \to J/\psi\,\phi$ but $B_s \to J/\psi\, f_0(980)$ is a pure CP-eigenstate
  - no angular analysis is required as in $B_s \to J/\psi\,\phi$
- CP-eigenstate (odd) mode with a final state with only 4 charged particles
- Expectations:
  - $\dfrac{B(B_s^0 \to J/\psi\ f_0)\,B(f_0 \to \pi^+\pi^-)}{B(B_s^0 \to J/\psi\ \phi)\,B(\phi \to K^+K^-)} \approx 0.2$ (Stone + Zhang [PRD 79, 074024])
  - $\dfrac{B(B_s^0 \to J/\psi\ f_0)\,B(f_0 \to \pi^+\pi^-)}{B(B_s^0 \to J/\psi\ \phi)\,B(\phi \to K^+K^-)} = 0.42 \pm 0.11$ (CLEO ($D_s \to f_0 e^+ \nu_e$) [PRD 80, 052009])

$$\rightarrow \boldsymbol{B(B_s^0 \to J/\psi\ f_0)\,B(f_0 \to \pi^+\pi^-) \approx (1.3 - 2.7) \times 10^{-4}}$$

  - $B(B_s^0 \to J/\psi\ f_0) = (3.1 \pm 2.4) \times 10^{-4}$ QCD (LO) [PRD 81, 074001]
    with $B(f_0 \to \pi^+\pi^-) = (50^{+7}_{-9})\%$ BES data [CLEO, PRD 80, 052009]

$$\rightarrow \boldsymbol{B(B_s^0 \to J/\psi\ f_0)\,B(f_0 \to \pi^+\pi^-) \approx (1.6 \pm 1.3) \times 10^{-4}}$$

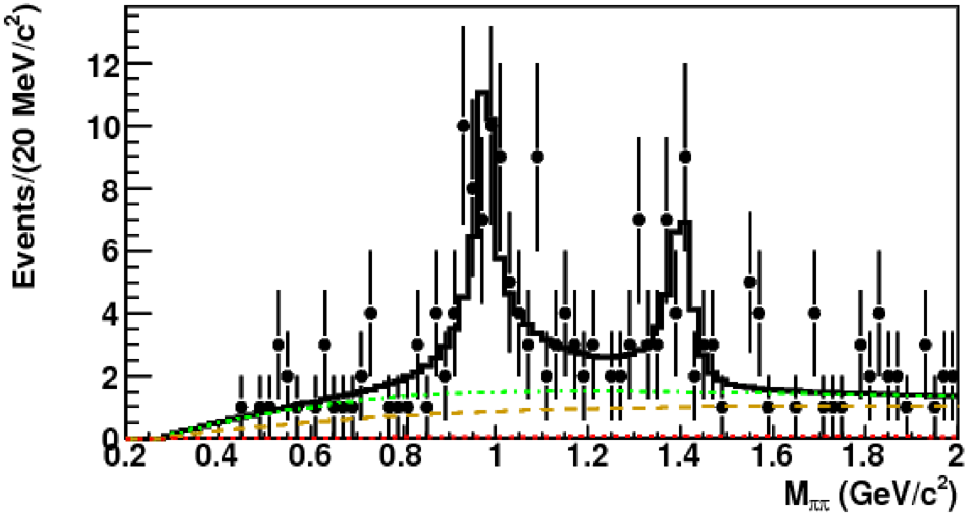
Search for $B_s^0 \to J/\psi\, f_0(980)$

Belle $(121\ \mathrm{fb}^{-1})$

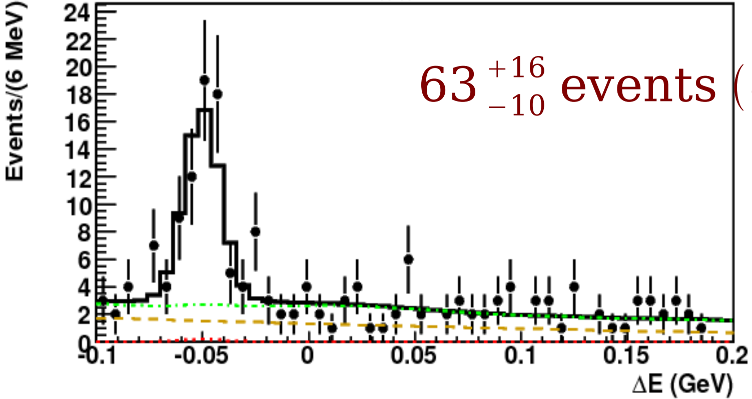
PRL 106, 121802 (2011)

- $J/\psi \to e^+e^-$ or $\mu^+\mu^-$, $f_0 \to \pi^+\pi^-$
- $(\Delta E, M_{\pi^+\pi^-})$ 2D fit in $-0.1\ \mathrm{GeV} < \Delta E < 0.2\ \mathrm{GeV}$ and $M_{\pi^+\pi^-} < 2.0\ \mathrm{GeV/c^2}$
- includes backgrounds from $B_s^0 \to J/\psi\, \pi^+\pi^-$ (peaks in ΔE) and other J/ψ modes

select events in $\Delta E \in [-0.08, -0.02]$ GeV

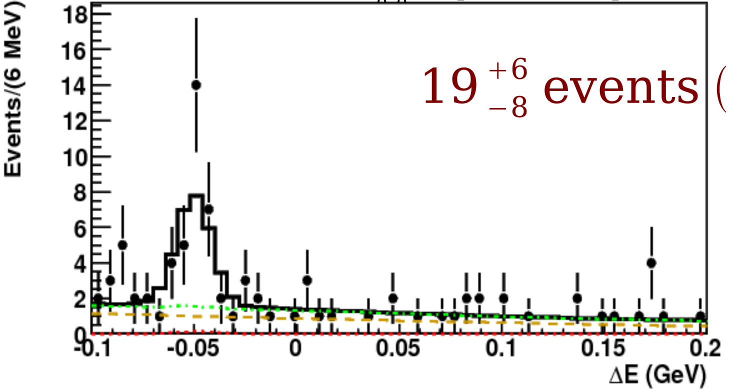


select events in $M_{\pi\pi} \in [0.80, 1.16]$ GeV/c²



$63\,^{+16}_{-10}$ events $(8.4\ \sigma)$

select events in $M_{\pi\pi} \in [1.3, 1.5]$ GeV/c²



$19\,^{+6}_{-8}$ events $(4.2\ \sigma)$

$$\mathcal{B}(B_s^0 \to J/\psi\, f_0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = (1.16\,^{+0.31}_{-0.19}(\mathrm{stat})\,^{+0.15}_{-0.17}(\mathrm{syst})\,^{+0.26}_{-0.18}(N_{B_s^{(*)}\bar{B}_s^{(*)}})) \times 10^{-4}\ (\text{at } 90\%\ \text{C.L.})$$

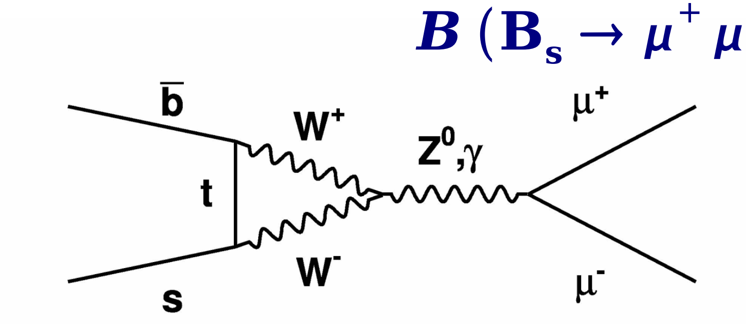
Motivation for BR measurements

- $B_s \rightarrow \mu^+ \mu^-$:

  sensitive probe to New Physics, very suppressed in SM:

  $$\boldsymbol{B}\,(\mathbf{B_s} \rightarrow \mu^+ \mu^-) = (\mathbf{3.35 \pm 0.32}) \times \mathbf{10^{-9}}$$

  [M.Blanke et al, hep-ph/0604057]



- NP can lead to enhancement of the BR up to an order of magnitude

  (for example, constrained versions of the MSSM $\sim 20 \times 10^{-9}$)

$\Rightarrow$ **BUT could be "only" a factor 2 above SM value !!**

- Need normalization with BR of $B_{(s)}$ decays
  - for example, Tevatron experiments use $B^+ \rightarrow J/\psi K^+$
  - $\sigma_{syst} \sim 13\%$: dominant error from $\dfrac{f(B_s)}{f(B)}$

$\Rightarrow$ **not sufficient if $\boldsymbol{B}\,(\mathbf{B_s} \rightarrow \mu^+ \mu^-) < \mathbf{10^{-8}}$**

- Need normalization mode meas with higher accuracy, preferably B_s mode

$\Rightarrow$ **measure B_s branching fraction in $\Upsilon(5S)$ decays !**

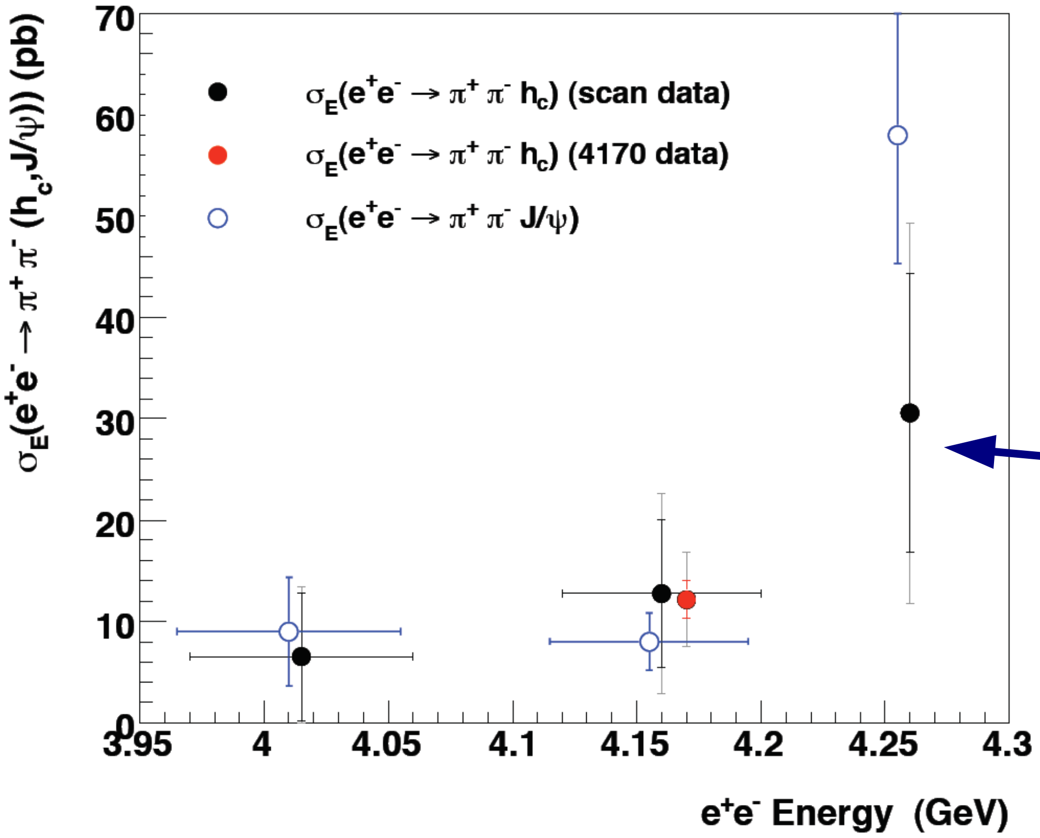
(for example $B_s \rightarrow J/\psi\,\phi$) so need to improve f_s

Trigger

Observation of $e^+e^- \to \pi^+\pi^- h_c$ above $D\,\overline{D}$ threshold by CLEO

Energy dependence of the cross-section

(R.Mitchell @ CHARM2010)



Production of h_c is unsuppressed relative to J/ψ

Enhancement at Y(4260) ?

Belle sees $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$,
so should search for $\Upsilon(5S) \to h_b\pi^+\pi^-$!

Bottomonium ground state η_b

Non-observation of the bottomonium ground state was an annoying thorn in the side of quarkonium spectroscopy. Finally, after 30 years of work

First measurement of η_b by BABAR in radiative Y(3S) and Y(2S) decays, followed by CLEO.

Measured parameters

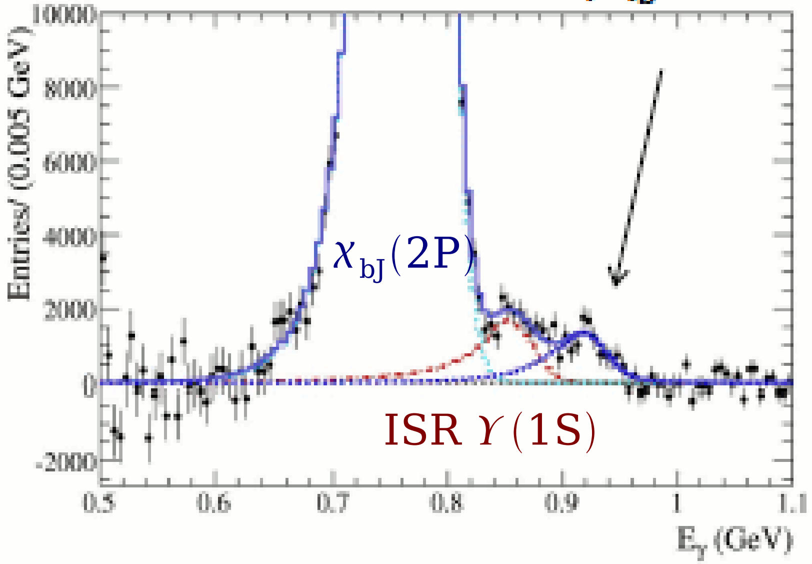
BF (Y(3,2S)→γ η_b) (10^{-4})	5.1 ± 0.7 / 3.9 ± 1.5
Y(1S) – η_b(1S) mass splitting:	69.3 ± 2.8 MeV

Hyperfine mass splitting predictions (MeV):

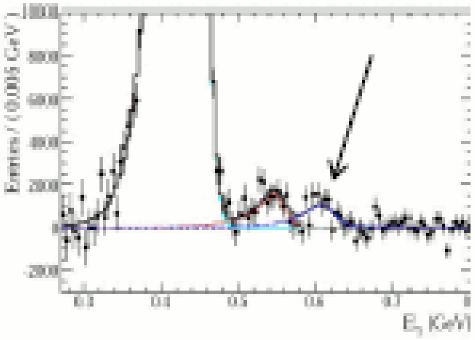
Potential models:	36-100 (36-87 recent models)
pNRQCD:	60.3 ± 5.5 ± 3.8 ± 2.1
Lattice QCD:	40-71

Confirmation from independent experiment or other decay channel desirable, as well as observation of η_b(2S)

BABAR Y(3S)→ γ η_b



BABAR Y(2S)→ γ η_b



CLEO Y(3S)→ γ η_b